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DYNAMIC SOILS INVESTIGATIONS. PROJECT BUGGY, BUCKBOARD MESA, NEVADA TEST SITE, MERCURY, NEVADA

Z. B. Fry

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS.

Foreword

The investigations described herein were requested verbally by the Embankment and Foundation Branch and the Geology Branch, Soils Division, U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, in connection with the investigations being performed for PROJECT BUGGY at the Nevada Test Site, Mercury, Nevada. The field investigations were performed from 7 through 10 February 1964.

Engineers of the WES who were actively engaged in the field investigations, analysis, and report phases of this study were Messrs. R. W. Cunny, Z. B. Fry, R. F. Ballard, Jr., and J. L. Decell of the Soils Division and Mr. H. C. Greer III of the Instrumentation Branch. The work was under the general supervision of Messrs. W. J. Turnbull and A. A. Maxwell, Chief and Assistant Chief, respectively, of the Soils Division. This report was prepared by Mr. Fry.

Col. Alex G. Sutton, Jr., CE, was Director of the WES during the conduct of the investigation and preparation and publication of this report. Mr. J. B. Tiffany was Technical Director.

Contents

Summary

Dynamic soils investigations were conducted at Buckboard Mesa, Nevada Test Site, Mercury, Nevada, to obtain data on the characteristics of subsurface materials underlying test locations proposed for cratering experiments. Specifically, the investigations were conducted to determine the feasibility of utilizing dynamic techniques to rapidly determine and delineate subsurface materials, thereby reducing the number of soil borings now required for such investigations. The investigations were performed in areas where borings had been previously made in order to compare results with known conditions and also in areas of unknown subsurface composition.

The investigations were conducted in two separate phases, i.e. seismic and vibratory, at four locations. Twelve seismic and four vibration traverses were made. The seismic traverses indicated very well the depth of overburden or topsoil and also the underlying vesicular basalt. However, discontinuities encountered in practically all of the seismic traverses, indicating the presence of low-velocity materials, cinder lenses, vertical fractures, etc., prevented such exploration to deeper depths, and it is doubtful that an underlying layer of dense basalt was actually encountered. The vibratory traverses were extended to greater depths than the seismic traverses and definite "breaks" could be seen in the shear velocity at these greater depths. The shear and compression moduli were also determined with vibratory traverses.

By integrating the results from the two methods of investigation, it was possible to prepare an approximate profile of materials in the area to depths of approximately 90 ft. However, a correlation of data obtained in the dynamic investigations and from borings at site 4 was not possible because of the erratic data obtained in the vibratory tests at this location.

It is concluded that dynamic techniques, such as those utilized in the investigations reported herein, can be used to rapidly determine the characteristics of subsurface materials such as those encountered in the Buckboard Mesa area.

DYNAMIC SOILS INVESTIGATIONS, PROJECT BUGGY
BUCKBOARD MESA, NEVADA TEST SITE
MERCURY, NEVADA

Background, Purpose, and Scope of Study

1. This report describes and presents the results of dynamic soils investigations performed in connection with PROJECT BUGGY, Buckboard Mesa, Nevada Test Site, Mercury, Nevada, to obtain data on the characteristics of the subsurface materials underlying selected test locations on Buckboard Mesa. Specifically, the investigations were conducted to determine the feasibility of utilizing dynamic techniques to rapidly determine the characteristics and layer thickness of subsurface materials, and thereby possibly reduce the number of soil borings now required for such investigations. The investigations were to be performed both in areas where borings had been made (in order to compare results with known conditions) and also in areas proposed for the PROJECT BUGGY crater experiments where borings had not been made.

Location and Description of Test Site

2. The test area, located on Buckboard Mesa, is approximately 50 miles north-northwest of Mercury, Nevada. The topography of the area and the test layout are shown in plate 1. The proposed site for PROJECT BUGGY is located in the central portion of the mesa near test sites 3 and 4 which are locations for other crater experiments. Sites 1 and 2 are areas investigated by the U. S. Army Engineer Waterways Experiment Station (WES).

3. The mesa rises rather abruptly to an elevation of approximately 5400 ft msl. The surface of the mesa is gently rolling terrain with numerous large boulders exposed over the entire area. Borings previously made near the proposed PROJECT BUGGY test area indicated a thin layer (about 5 ft) of residual topsoil underlain by vesicular basalt varying from 35 to 90 ft in thickness changing to gray, hard, dense basalt below the vesicular layer (plate 2). The basalts are interspersed with numerous lenses of cinders and vary from highly to moderately to slightly fractured zones.

Tests and Test Methods

4. The dynamic investigations were conducted in two separate phases: seismic and vibratory. Each phase was designed to reveal specific information on the physical properties of the soil underlying the test area. The tests were performed in accordance with methods described in Appendix A.

5. The investigations were conducted at four locations: sites 1, 2, 4, and BUGGY 2 (plate 1). The tests at site 1 consisted of three seismic traverses (S-1, S-2, and S-3) and one vibratory traverse (V-3). The traverses were run on a southeasterly line from NCG 2.1 to site 4, just north of and parallel to the site 4 access road. The tests at site 2 consisted of six seismic traverses (S-6 and S-7, S-5 and S-8, and S-9 and S-10) and two vibratory traverses (V-5 and V-9). The seismic traverses in this area were reverse traverses, e.g. S-6 and S-7 were conducted in opposite directions over the same line. The site 2 area was just south of the access road to site 4 and was indicated as that area in which the PROJECT BUGGY tests were to be conducted. One seismic traverse (S-4) and one vibratory traverse (V-4) were run in the vicinity of site 4. Two seismic traverses (S-11 and S-12) were conducted at BUGGY 2. BUGGY 2 was a borehole previously drilled for subsurface exploration, but the area was considered undesirable for the proposed PROJECT BUGGY tests. Both the seismic and vibration traverses were conducted along lines extending 100 ft or more.

6. As previously stated, the area was covered with large exposed boulders which prevented access with the vibratory equipment to the areas of seismic traverses S-1 near NCG 2.1 and S-11 and S-12 at BUGGY 2. Investigations were concentrated at site 2 since this was believed to be a satisfactory location for PROJECT BUGGY.

Results of Tests

Site 1

7. The results of the three seismic traverses conducted at site 1 are shown in plates 3 through 5. Traverse S-1 (plate 3) indicates a velocity of 1425 fps in the near-surface materials to a depth of 4.2 ft. Below 4.2 ft the velocity increases to 3455 fps; however, a discontinuity occurs

at a distance of about 60 to 90 ft (see plate 3) from the geophone location and again at about 125 ft, where the velocity decreases to 1460 fps.

8. The results of traverses S-2 and S-3 (plates 4 and 5) indicate a velocity of 1050 fps for the near-surface materials to depths of 4.6 and 5 ft, respectively. There appears to be a transition zone along S-2 in which the velocity increases to 1940 fps from depths of 4.6 to 16.5 ft. Along S-3, the velocity increases to 1750 fps below 5 ft. Below the 16.5-ft depth along S-2, the velocity increases to 4000 fps. There is a discontinuity on traverse S-3 at about 30 ft from the geophone location, but a velocity of 6250 fps is obtained between 60 and 100 ft from the geophone location.

9. The vibratory traverse V-3 was conducted along the same line as seismic traverse S-3. Plates 6 and 7 present results of the velocity determinations and velocity versus depth, respectively. The shear velocity increases from approximately 250 fps near the surface to 940 fps at a depth of 10 ft. The increase in velocity is then more gradual to 1300 fps at a depth of 26 ft. There appears to be a definite "break," or change, in the shear velocity at approximately 10 ft from the surface.

Site 2

10. At site 2 traverses S-6 and S-7, S-5 and S-8, and S-9 and S-10 were run along a line extending 300 ft from northwest to southeast. The results of the seismic tests are shown in plates 8 through 10. The velocity in the near-surface material was 1050 to 1100 fps, except for traverse S-7 which indicated a velocity of 1750 fps. There is some discontinuity indicated by traverses S-6 and S-7. Near the southeast end of these traverses, the terrain began to rise sharply and no doubt had a considerable amount of the fractured rock interspersed with the residual top soil. There are also indications of discontinuities at the northwest end of traverses S-9 and S-10 where the rock is apparently nearer the surface. The velocities obtained in the material below the 6- to 10-ft depths varied considerably. Traverses S-9 and S-10 indicate a transition zone from 4 to 18 ft with velocities of 1500 to 2000 fps, and below 18 ft, velocities of 4500 fps. The velocities obtained from traverses S-5 and S-8, and S-6 ranged from 2500 to 4000 fps below the 6- to 10-ft depths.

11. The vibratory traverses V-5 and V-9 were conducted along the

same line as seismic traverses S-5 and S-8, and S-9 and S-10. The results of V-5 and V-9 (plates 11 through 14) indicate that the velocity increases from approximately 250 near the surface to 1200 fps at a depth of 15 ft. The velocity remains relatively uniform below 15 ft, i.e. from 1050 to 1150 fps from 15 to 40 ft for traverse V-5, and from 1200 to 1400 fps from 15 to 54 ft for traverse V-9. Below the 40- and 50-ft depths, the velocity gradually increases to approximately 1900 fps at depths of 93 and 90 ft for V-5 and V-9, respectively.

Site 4

12. The area at site 4 had been previously prepared for a test similar to the proposed PROJECT BUGGY. The area had been thoroughly investigated and was considered to be a satisfactory site for cratering tests.

13. The surface around site 4 had been graded and cleared of practically all topsoil, and many large boulders or rock surfaces were visible at the surface. Seismic traverse S-4 was conducted in a northwest direction from site 4 and the results (plate 15) indicate a velocity of 2300 fps to a depth of 6.5 ft, increasing to 4000 fps below that depth. A discontinuity occurs at about 80 ft from the geophone and the velocity then decreases considerably to about 1250 fps.

14. A vibratory traverse V-4 was conducted along the same line as S-4, and the results (plates 16 and 17) are very erratic; only the values obtained at the low frequencies (12 to 20 cps) are considered valid. Measurements were attempted with numerous other frequencies from 20 to 100 cps, but the signals were very distorted and measurements could not be made. The higher frequencies were equally erratic; only two velocity values were obtained and these may be questionable. The lower frequencies produced velocities ranging from 1720 fps at 43 ft to 2100 fps at 88 ft. A boring log (from previous tests) for the site 4 area is provided in plate 17 to illustrate the subsurface conditions.

BUGGY 2

15. The BUGGY 2 site was an area in which a boring had previously been made for subsurface exploration in connection with proposed site selection for PROJECT BUGGY. Two seismic traverses (S-11 and S-12) were conducted in opposite directions at the site, overlapping the borehole by about 20 ft. The results (plates 18 and 19) indicate a velocity of 1600 fps

in the near-surface topsoil to depths of 3.1 to 3.5 ft, increasing to 2750 to 3000 fps below those depths. Discontinuities began to appear about midway of both traverses. Vibratory traverses could not be conducted in this area as large boulders on the surface prevented access with the equipment.

Discussion of Results

16. The results of the dynamic tests, both seismic and vibratory, indicated that considerable stratifications or discontinuities exist in the subsurface materials in the areas investigated. The seismic traverses usually indicated only the compression velocity and the thickness of the topsoil or near-surface layer. Below the near-surface layer, discontinuities encountered in practically all of the seismic traverses, except S-5 and S-8, indicated the presence of low-velocity materials, cinder lenses, vertical fractures, or abrupt change in depth of underlying materials. The seismic traverses conducted at sites 1, 4, and BUGGY 2 indicate a layer of topsoil from 3 to 6.5 ft in depth. These depths are well validated by results of the borings conducted at site 4 and BUGGY 2.(see plates 17 through 19), which indicate similar depths of overburden. At site 2 the seismic traverses indicated a gradual dip in the underlying rock from northwest to southeast, increasing from about 4 ft at the northwest end of traverse S-9 and S-10 to about 10 ft at a point midway on traverse S-6 and S-7. The velocities in the range of 2500 to 4000 fps obtained at sites 1, 2, 4, and BUGGY 2 are believed to be representative of the vesicular basalt in the area. This is further validated by the logs of borings for BUGGY 2 and site 4, plates 17 through 19. It is doubtful that the dense basalt was actually encountered except perhaps with traverse S-3 at site 1 for which a velocity of 6250 fps was obtained at some undeterminable depth (plate 5). Normally, compression velocities of 8000 to 13,000 fps are expected for dense basalt.

17. The vibratory traverses by which a shear velocity was determined extended the exploration to greater depths than could be reached with the seismic traverses. Definite "breaks" could be seen in the velocity versus depth plots for sites 1 and 2 (plates 7, 12, and 14), and materials believed

to be present at various depths were designated. The information from vibratory traverses was also utilized in conjunction with that obtained from the seismic traverses to construct an approximate profile of materials for the areas investigated (plate 20). The vibratory traverse conducted at site 4 produced some rather erratic results, and measurements could not be obtained to indicate the satisfactory test conditions previously indicated by the boring made in the area. The boring log, shown in plate 17 in conjunction with results of traverse V-4, does not indicate particularly variable subsurface conditions; however, the traverse was conducted along a line from 35 to 135 ft northwest of the boring, and it is possible that conditions may have changed.

18. The results of the vibratory tests were further utilized to determine the shear moduli G and compression (Young's) moduli E in accordance with methods outlined in Appendix A. To determine these moduli, values of Poisson's ratio and density of the materials had to be obtained or assumed. Samples of the subsurface materials had been previously obtained, and laboratory tests were conducted by the WES Concrete Division. The following values were found to be applicable to the depths shown:

Depth, ft	Density lb/cu ft	Poisson's Ratio
0 to 10	95	0.25
10 to 50	145	0.20
50+	170	0.20

The values of Poisson's ratio appear to be somewhat low, but even doubling the values would not affect the results more than 5 percent. Using the preceding values in conjunction with the previously determined shear velocities for corresponding depths, the compression and shear moduli were determined for traverses V-3, V-5, V-9, and V-4 and are plotted versus approximate depth in plates 21 through 24. Also shown in these plates are the limits of the materials believed to be indicated by the data. The delineation of the depths of the different subsurface materials is made with the knowledge that such particular materials exist as previously determined by numerous borings in the area. If this knowledge had not been available, specific designations such as vesicular basalt and dense basalt could not

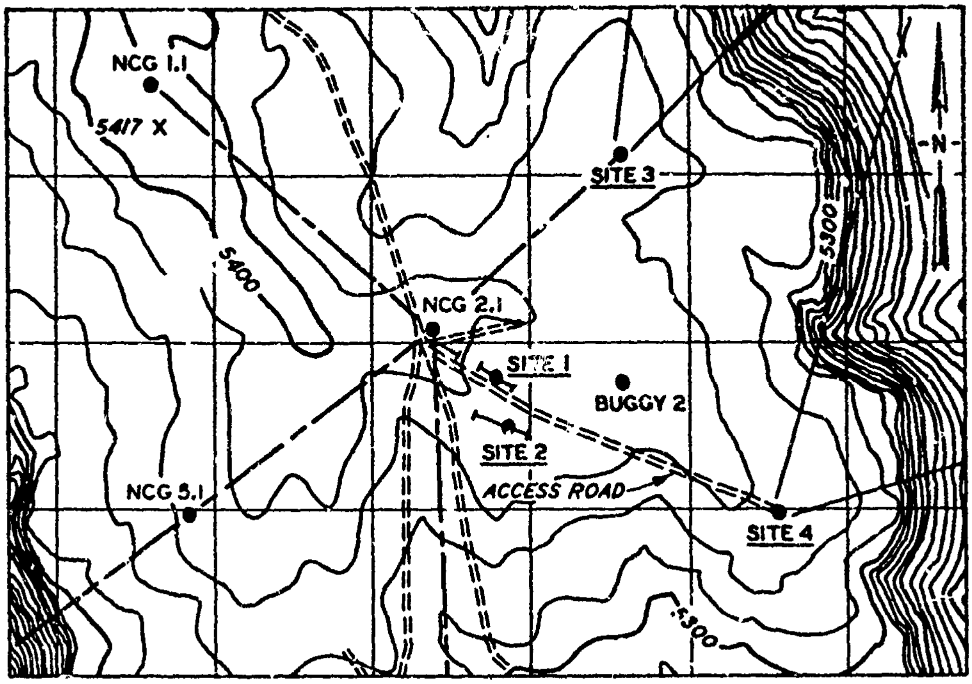
have been made and only the apparent changes in materials could be shown.

Conclusions

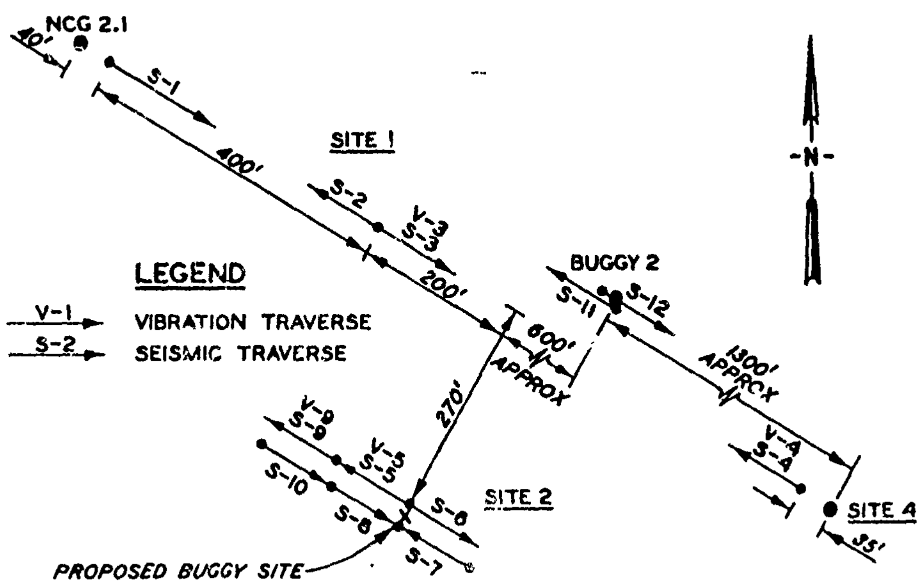
19. The results of the investigations indicate that dynamic methods can be used to rapidly determine the characteristics of subsurface materials such as those encountered in the Buckboard Mesa area. The seismic investigations indicated very well the velocity and thickness of the topsoil and the velocity of the vesicular basalt. The vibratory techniques provided a means of extending the depth of investigation at sites 1 and 2. The correlation between vibratory and boring data was not conclusive for site 4, the area previously determined to be "satisfactory." The area deemed most satisfactory from results of these tests was site 2, although site 1 also was considered to be acceptable.

Recommendation

20. It is recommended that exploratory borings be made at sites 1 and 2 to provide a means for correlation of the predicted and actual subsurface characteristics of these areas.



a. GENERAL TOPOGRAPHY OF AREA



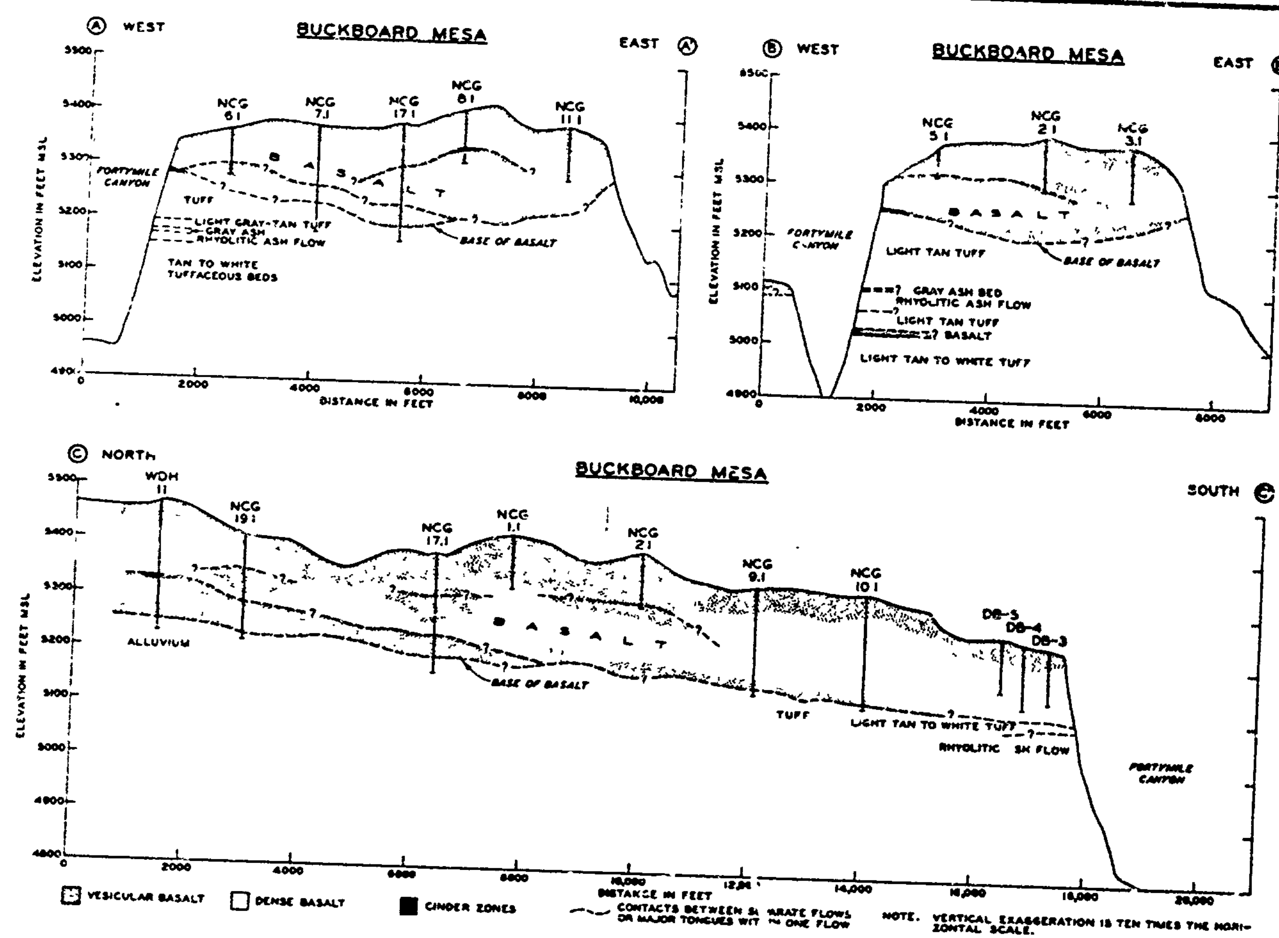
b. TEST LAYOUT

SCALE IN FEET

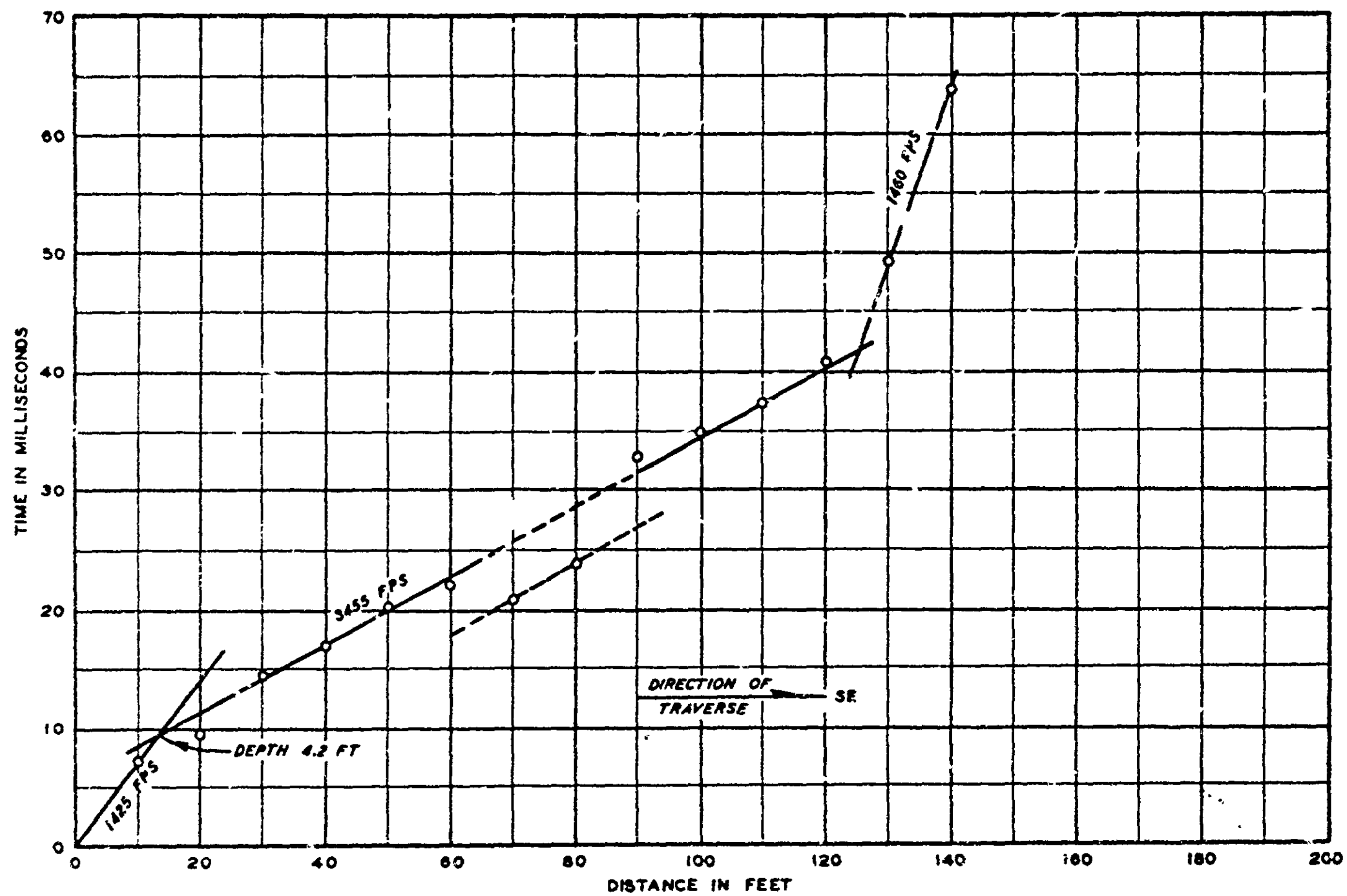
100 0 100 200

AREA TOPOGRAPHY AND
TEST LAYOUT

PLATE 2

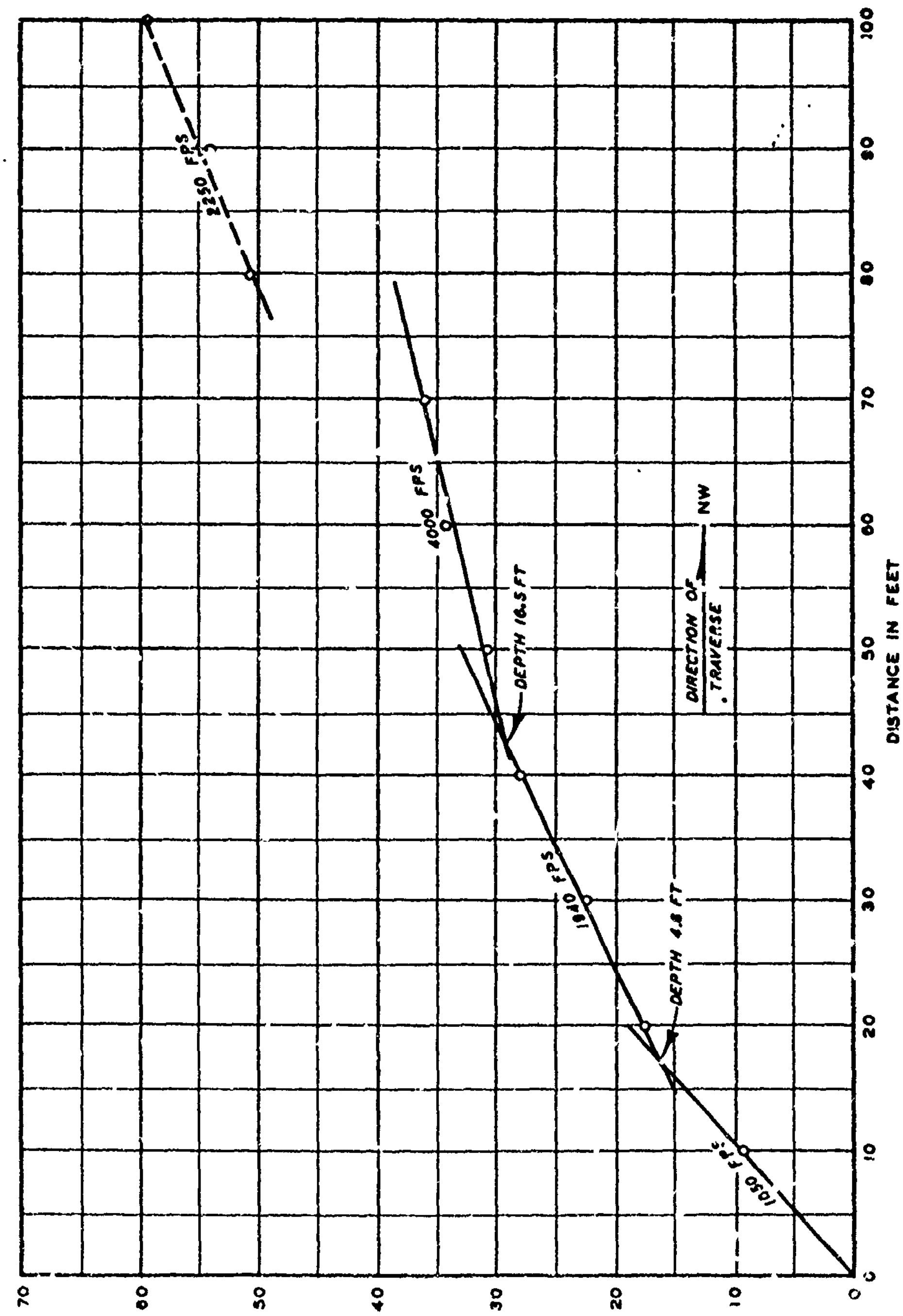


GENERAL SECTION
BUCKBOARD MESA



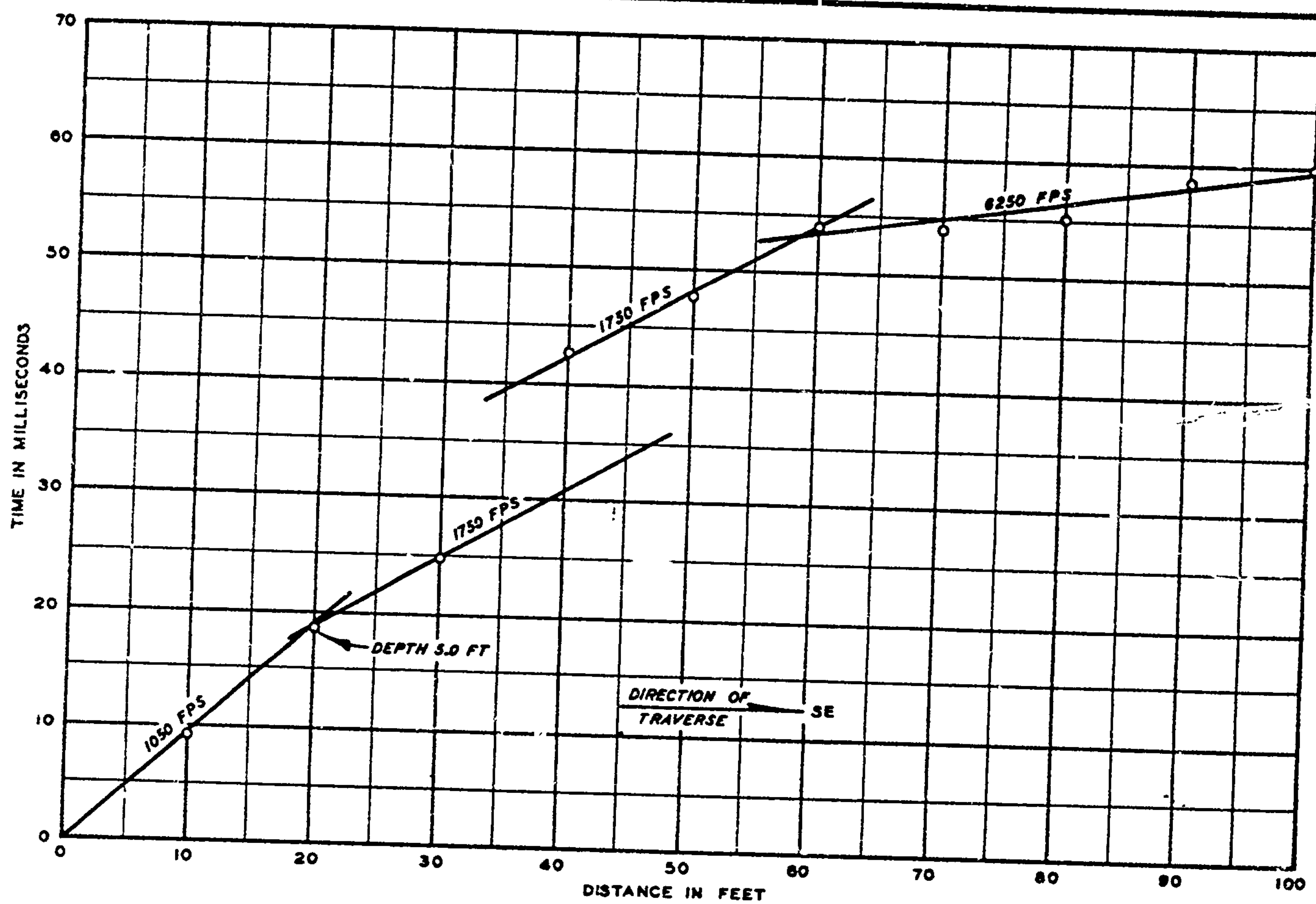
VELOCITY DETERMINATIONS
FROM SEISMIC TESTS

TRAVERSE S-1



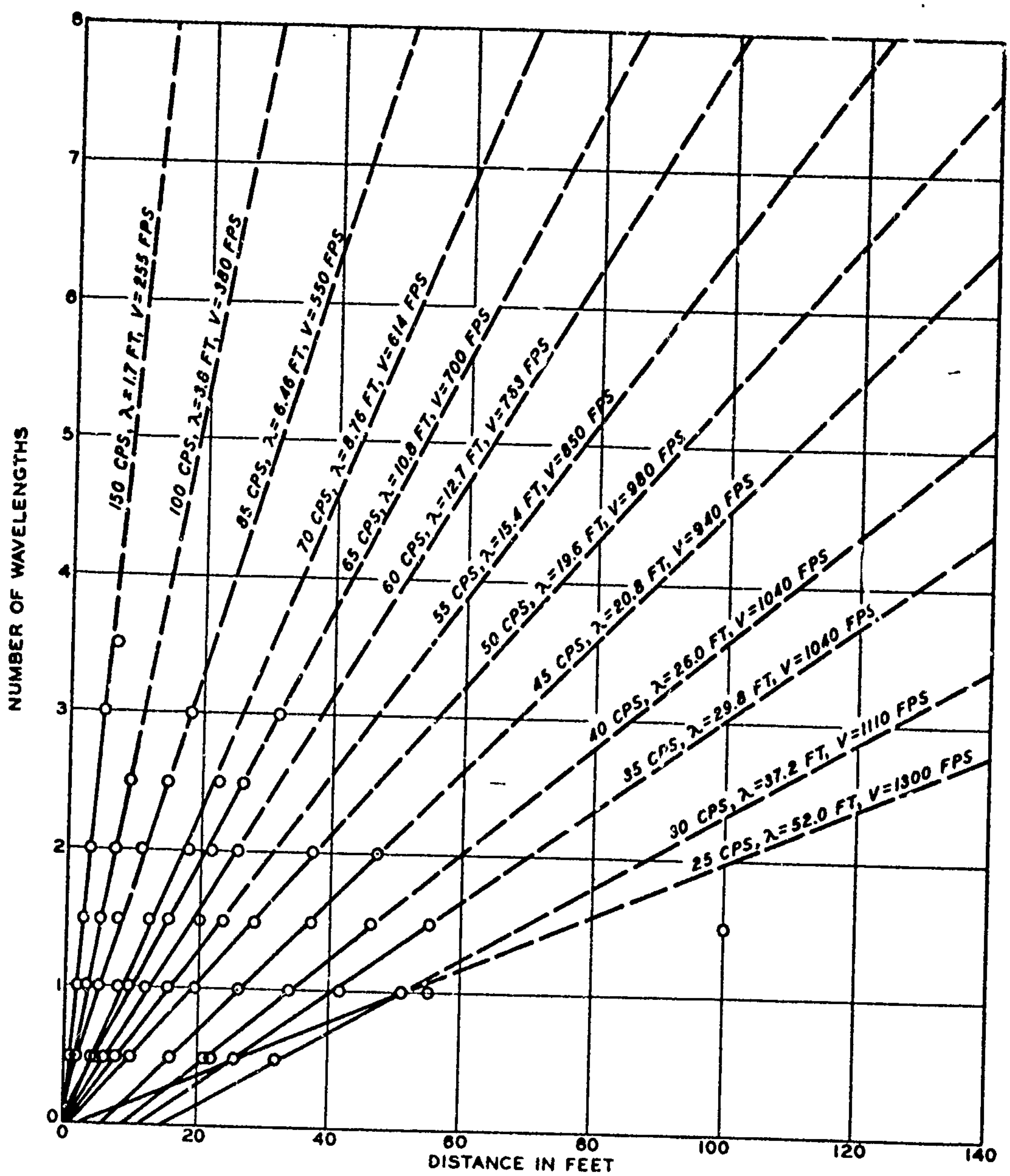
VELOCITY DETERMINATIONS FROM SEISMIC TESTS

TRAVERSE S-2



VELOCITY DETERMINATIONS
FROM SEISMIC TESTS

TRAVERSE S-3

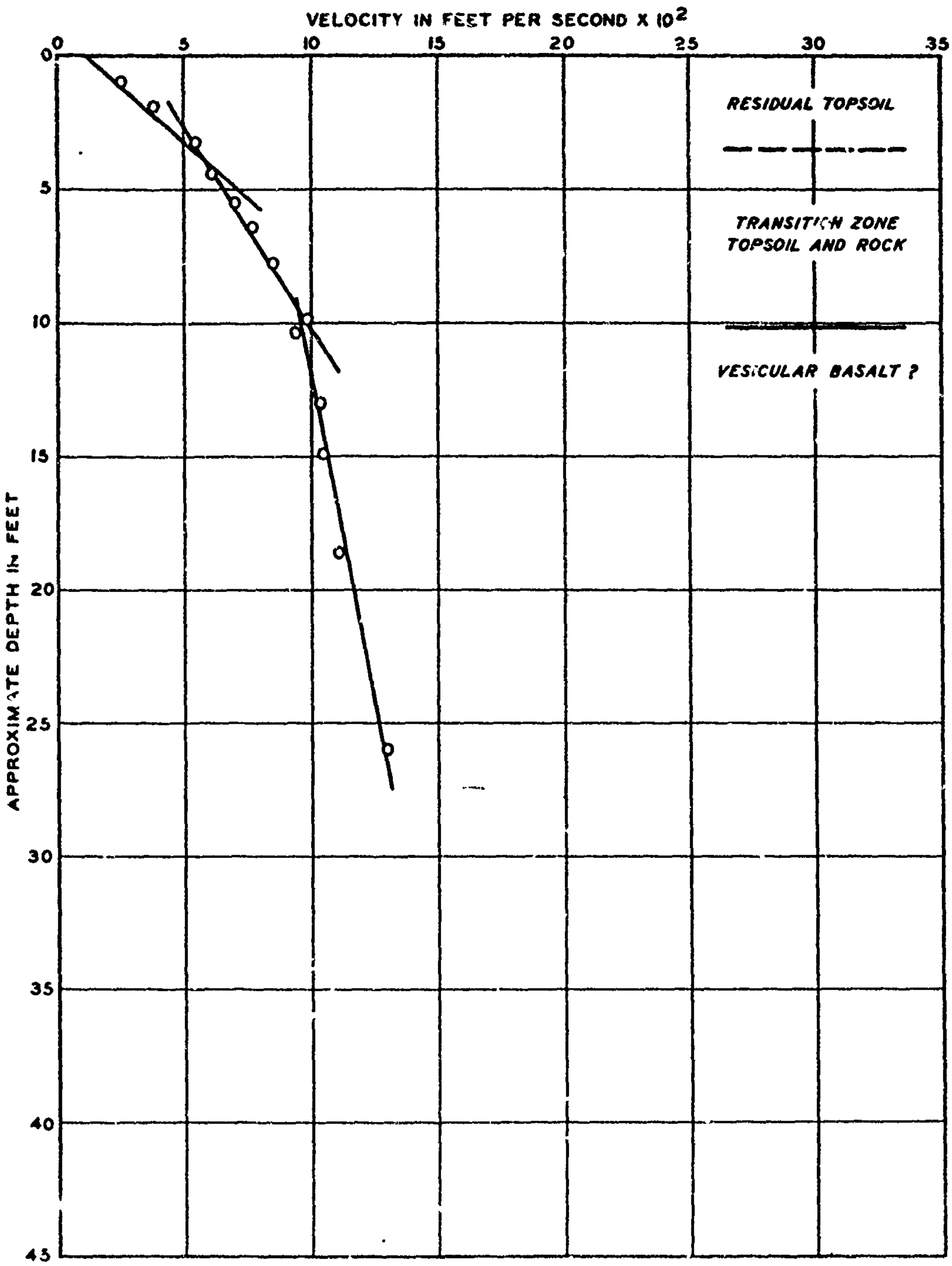


NOTE: λ = WAVELENGTHS
V = WAVE VELOCITY

VELOCITY DETERMINATIONS FROM VIBRATORY TESTS

TRAVERSE V-3

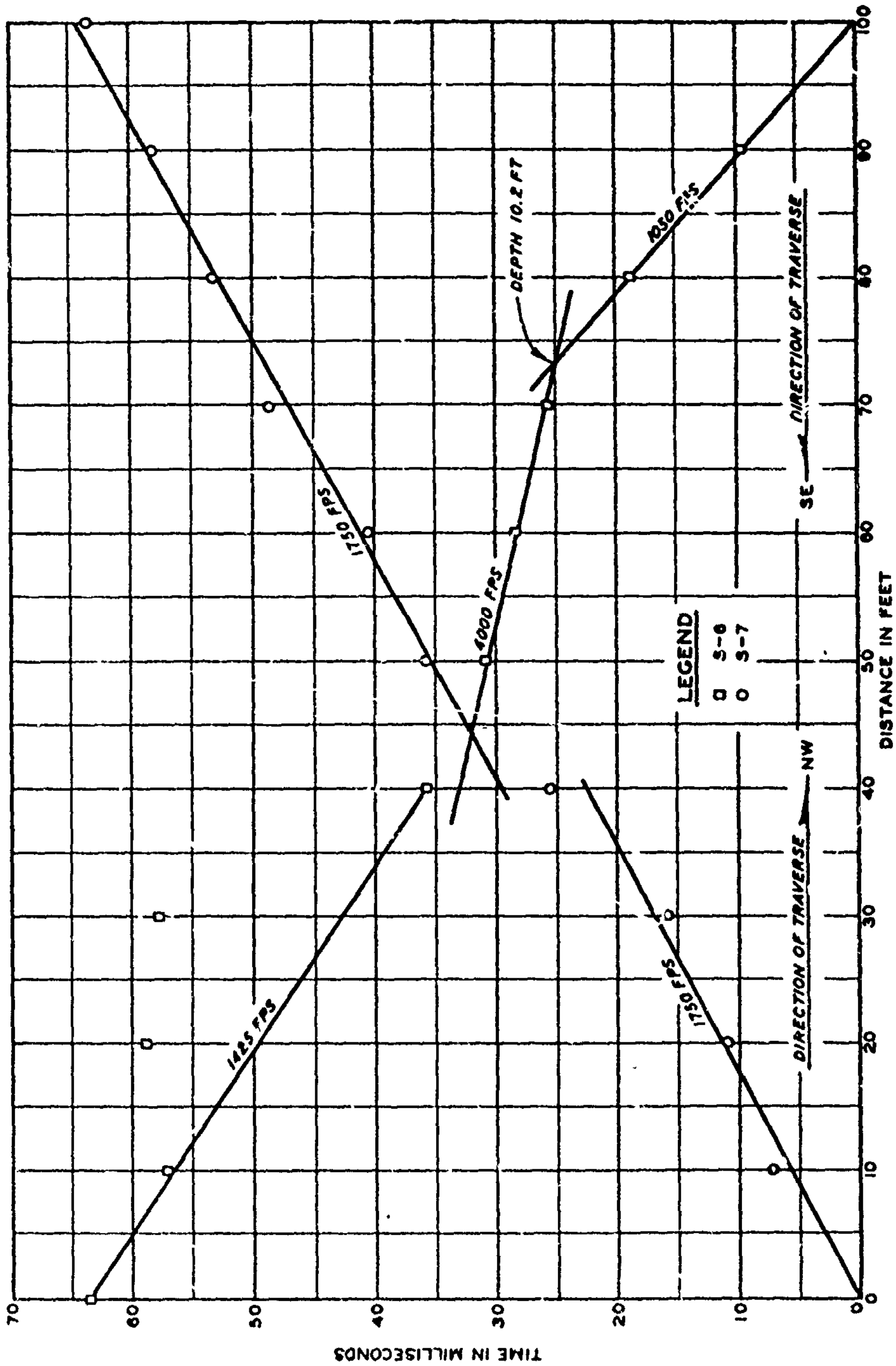
PLATE 5



VIBRATORY VELOCITY
VS DEPTH

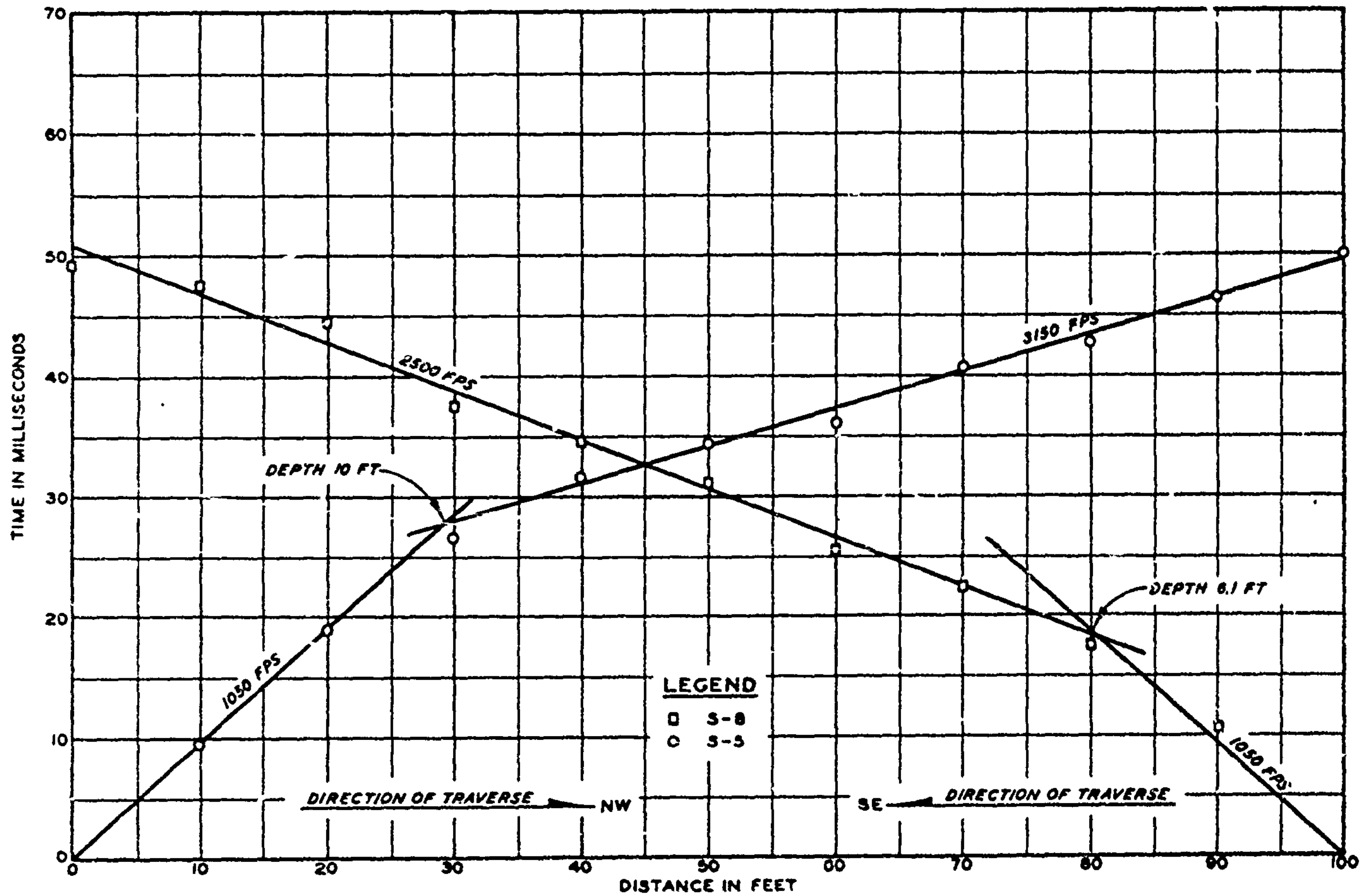
TRAVERSE V-3

PLATE 7



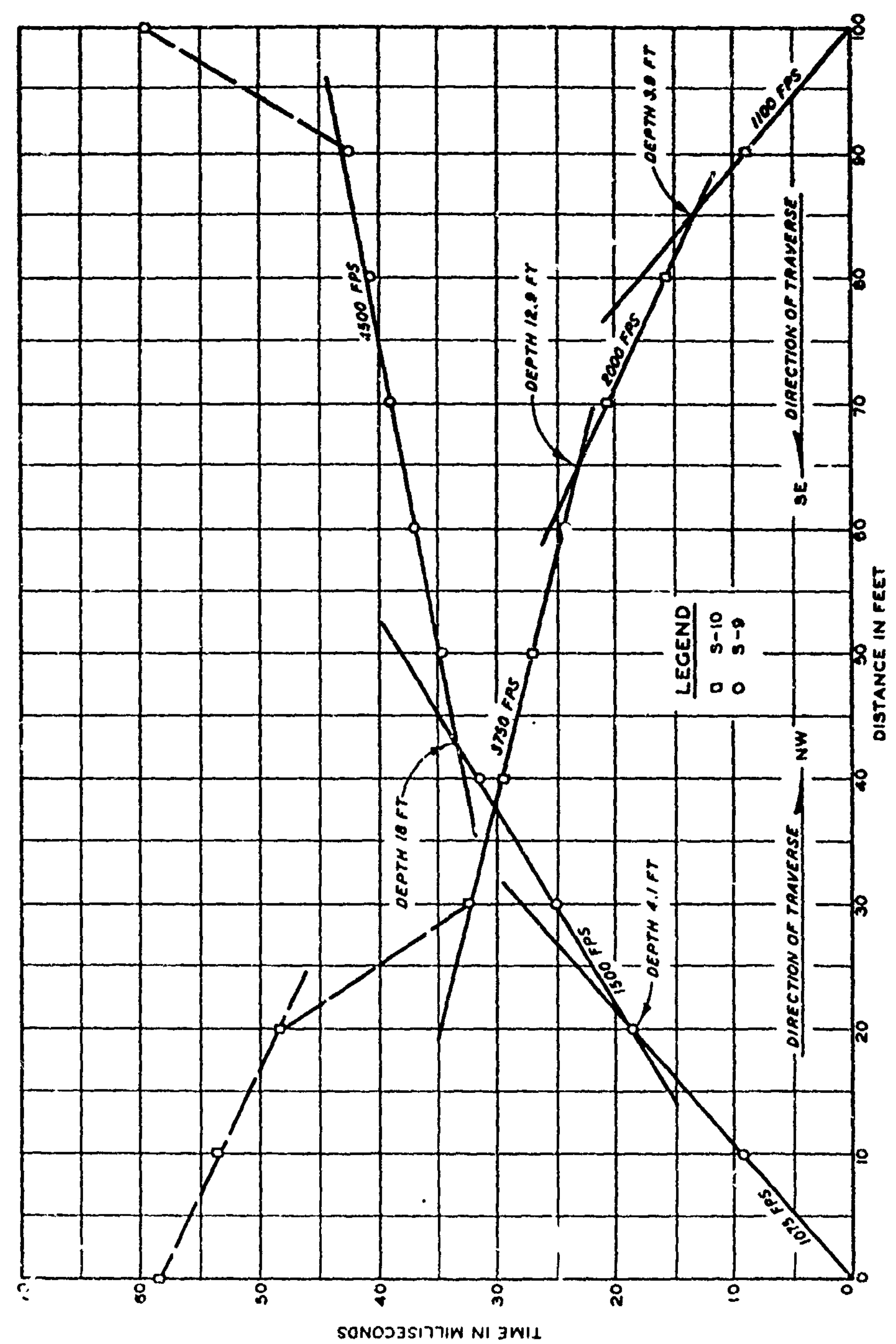
VELOCITY DETERMINATIONS FROM SEISMIC TESTS
TRAVERSES S-6 AND S-7

PLATE 8



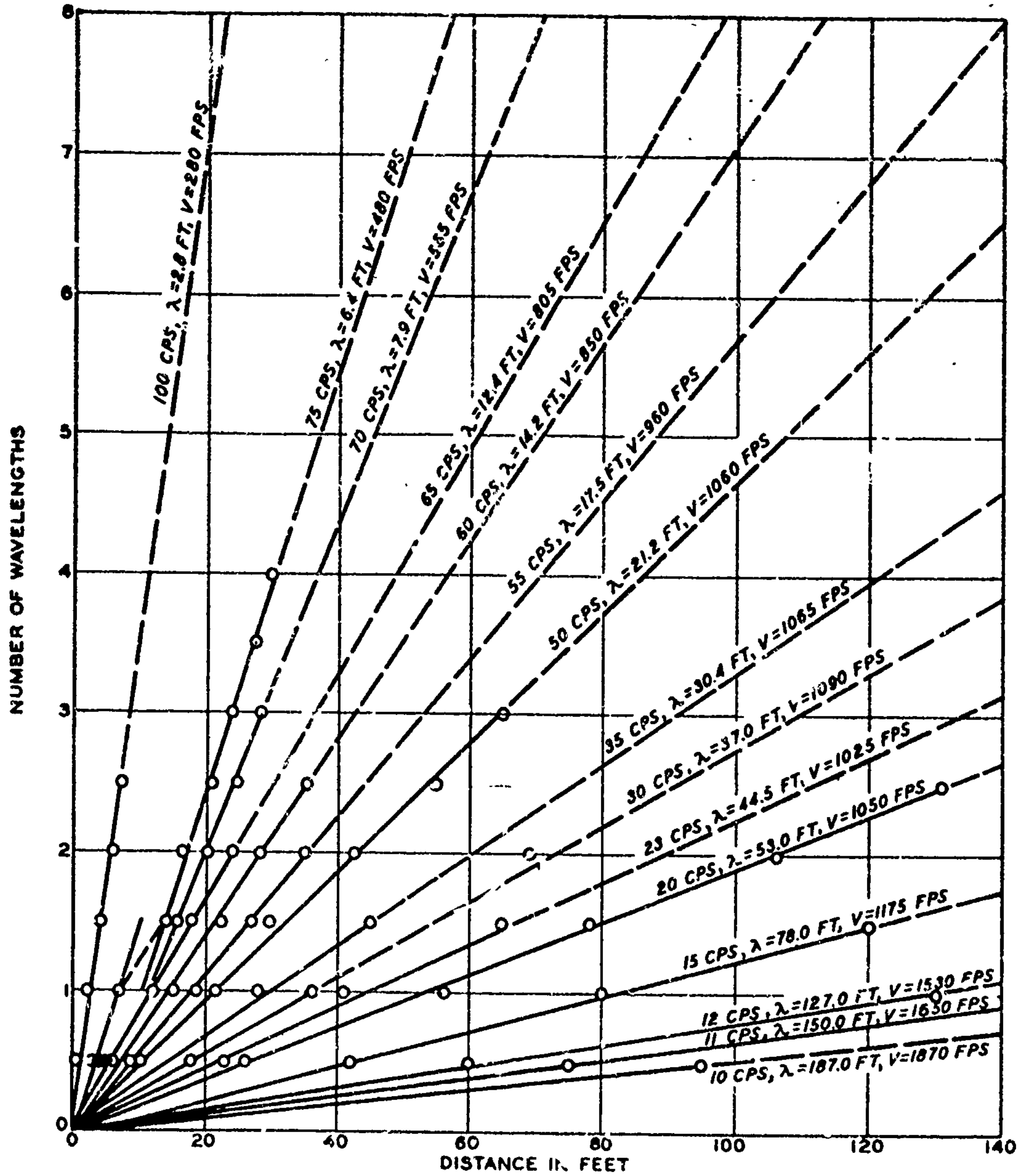
VELOCITY DETERMINATIONS FROM SEISMIC TESTS

TRAVERSES S-5 AND S-8



VELOCITY DETERMINATIONS
FROM SEISMIC TESTS
TRAVERSES S-9 AND S-10

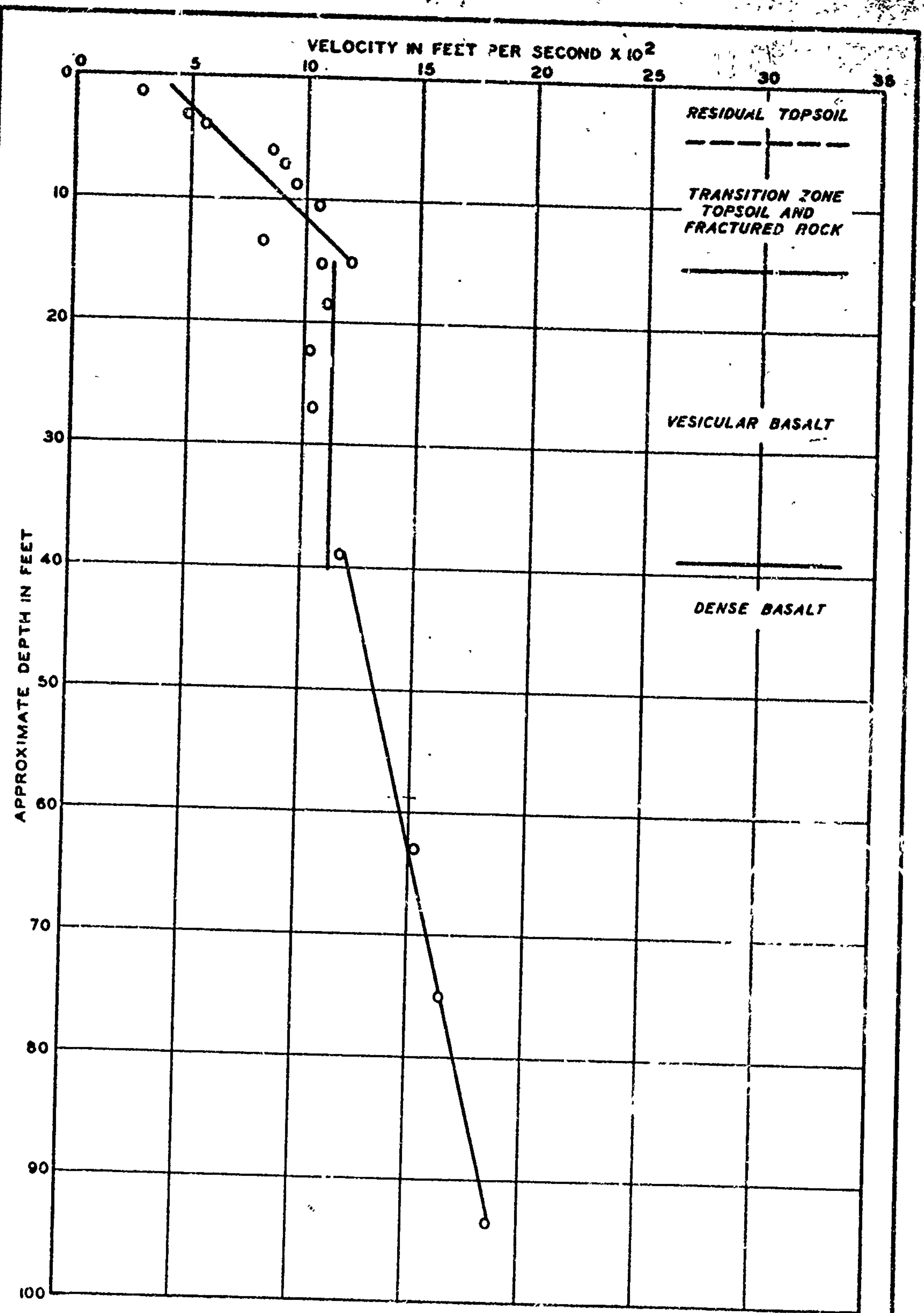
PLATE 10



NOTE: λ = WAVELENGTHS
V = WAVE VELOCITY

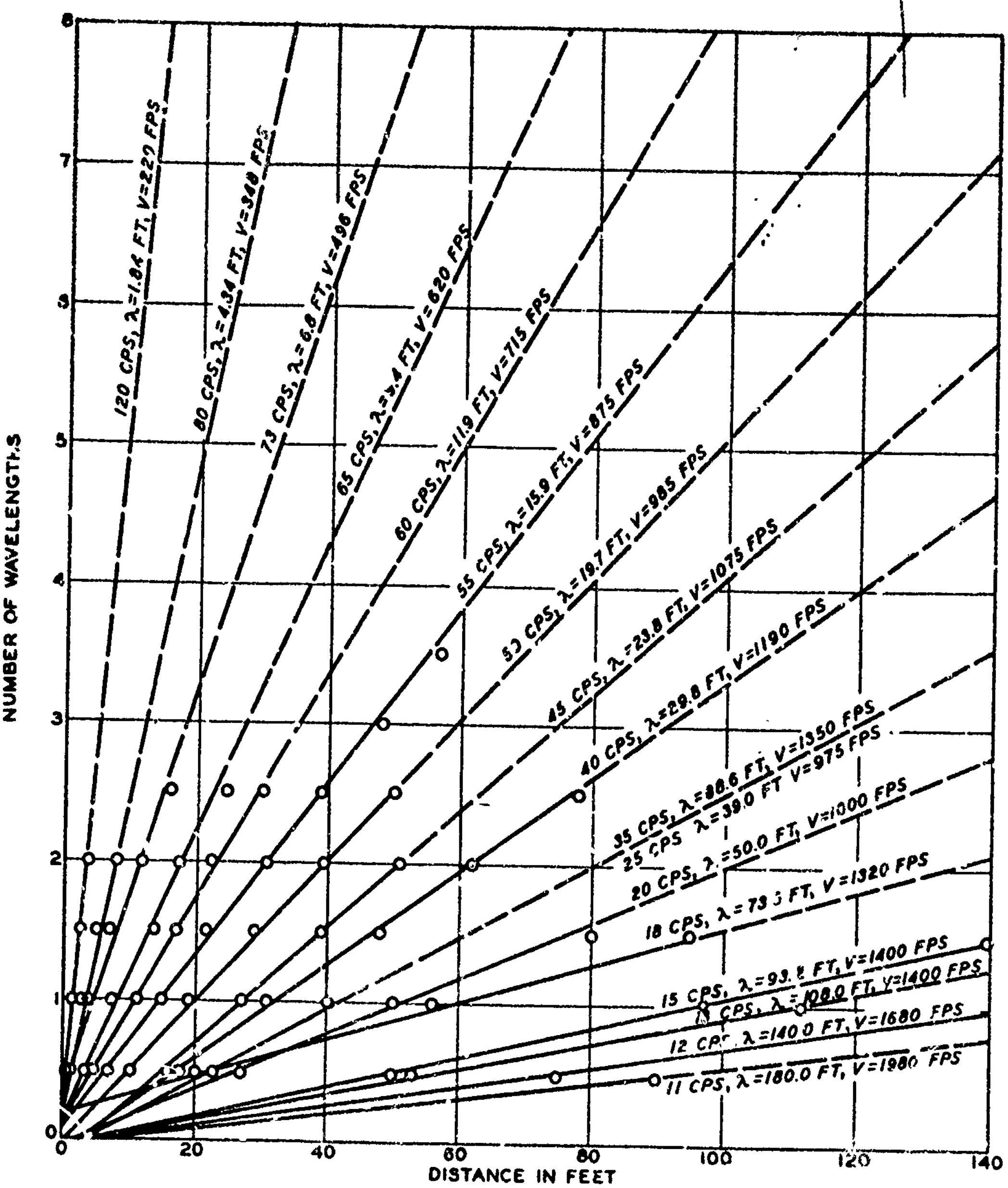
VELOCITY DETERMINATIONS FROM VIBRATORY TESTS

TRAVERSE V-5



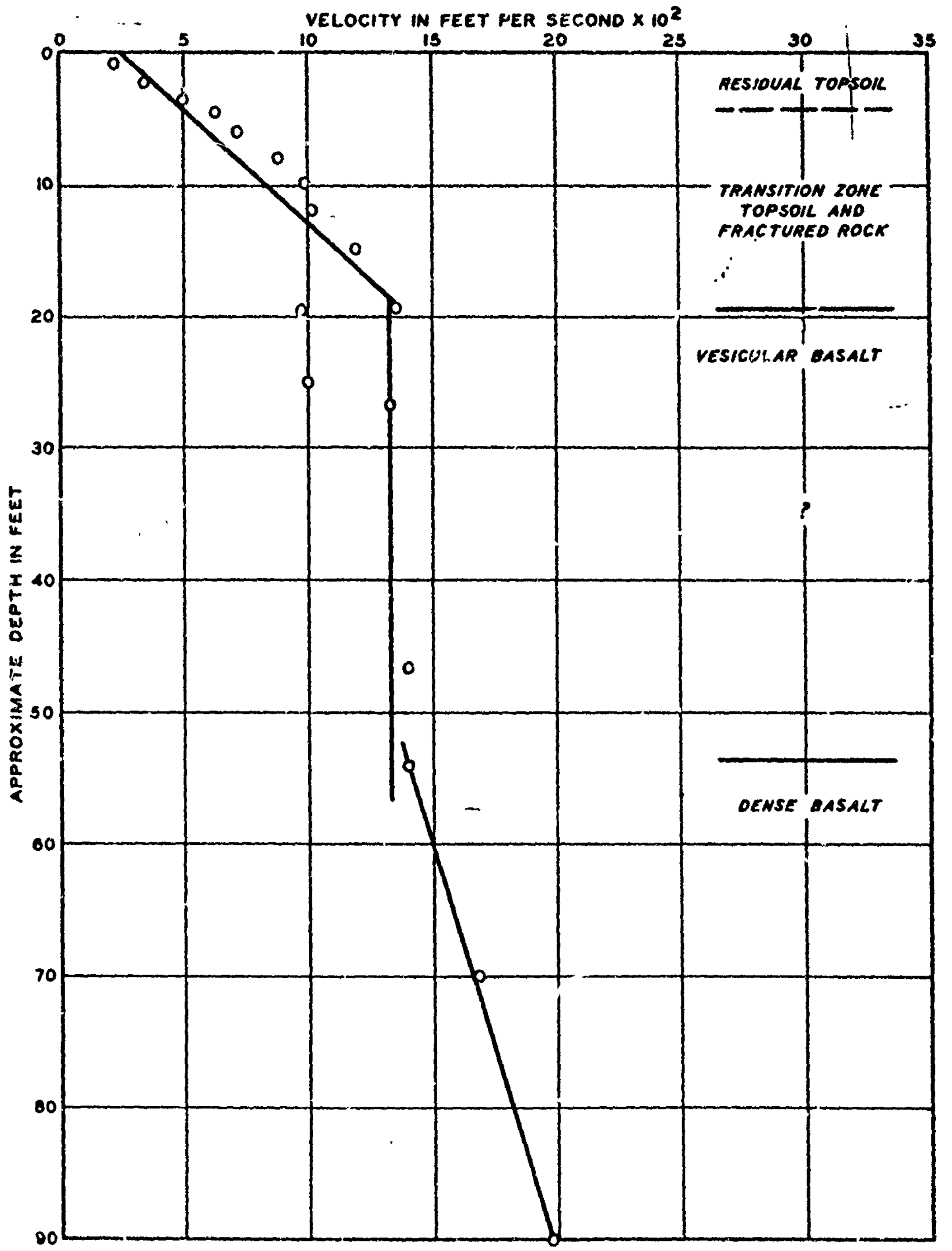
VIBRATORY VELOCITY
VS DEPTH
TRAVERSE V-5

PLATE 12



NOTE: λ = WAVELENGTHS
V = WAVE VELOCITY

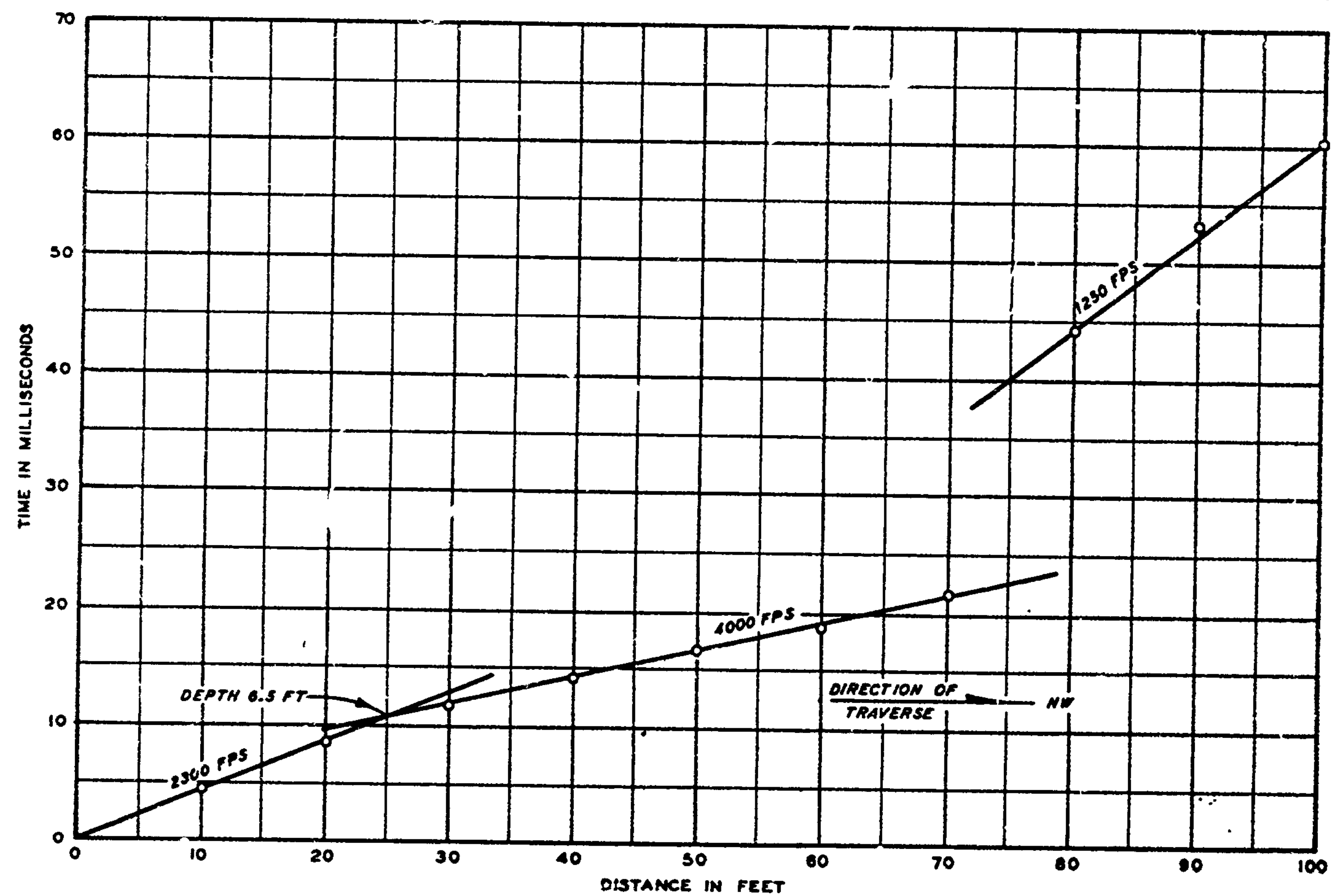
VELOCITY DETERMINATIONS
FROM VIBRATORY TESTS
TRAVERSE V-9



VIBRATORY VELOCITY
VS DEPTH

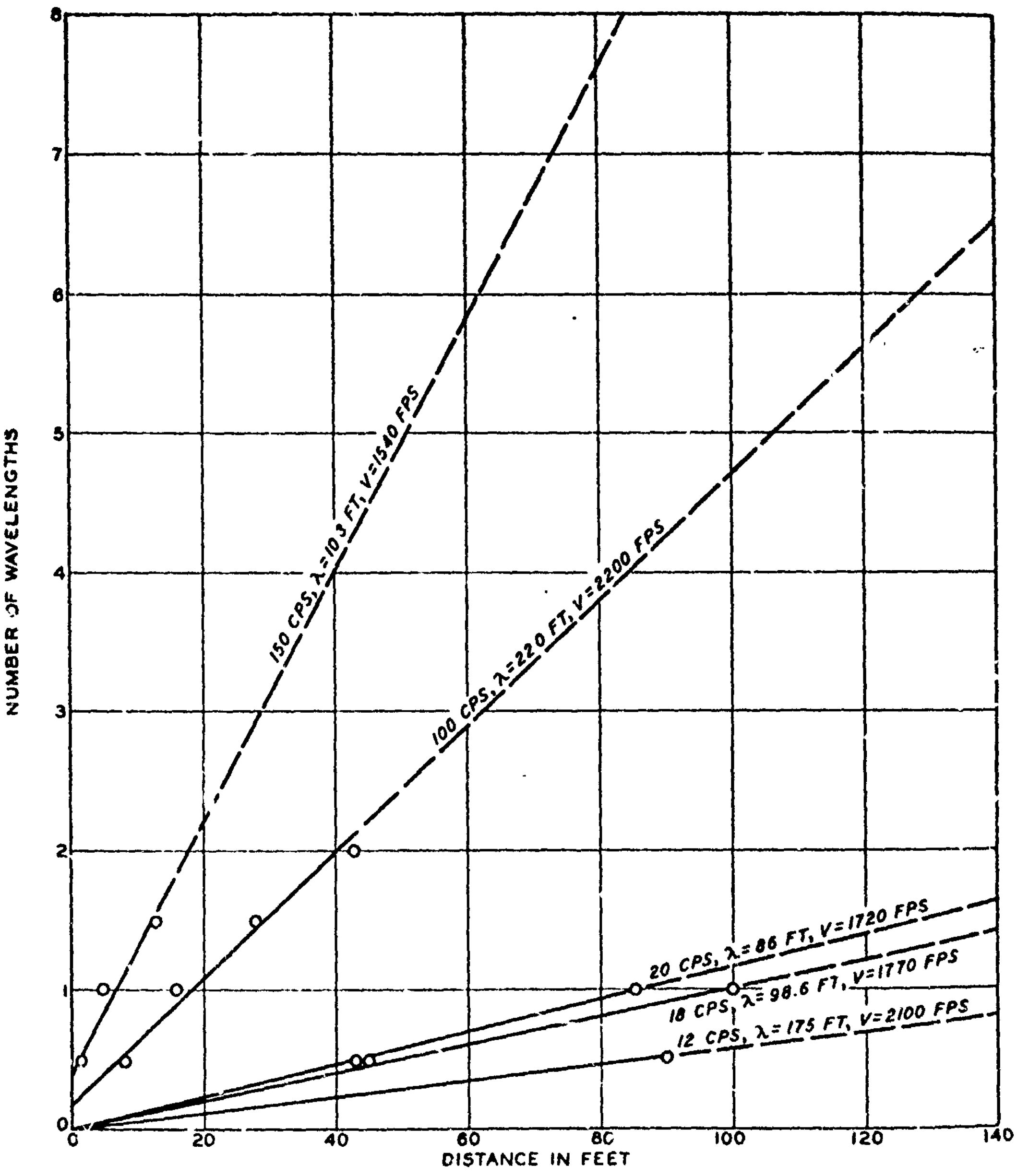
TRAVERSE V-9

PLATE 14



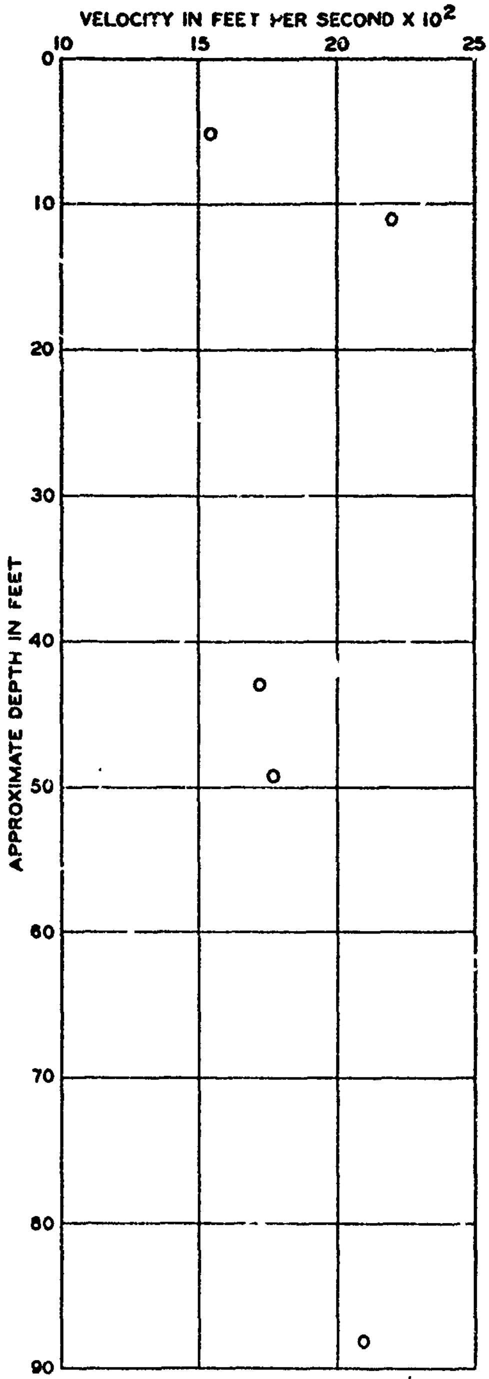
VELOCITY DETERMINATIONS
FROM SEISMIC TESTS

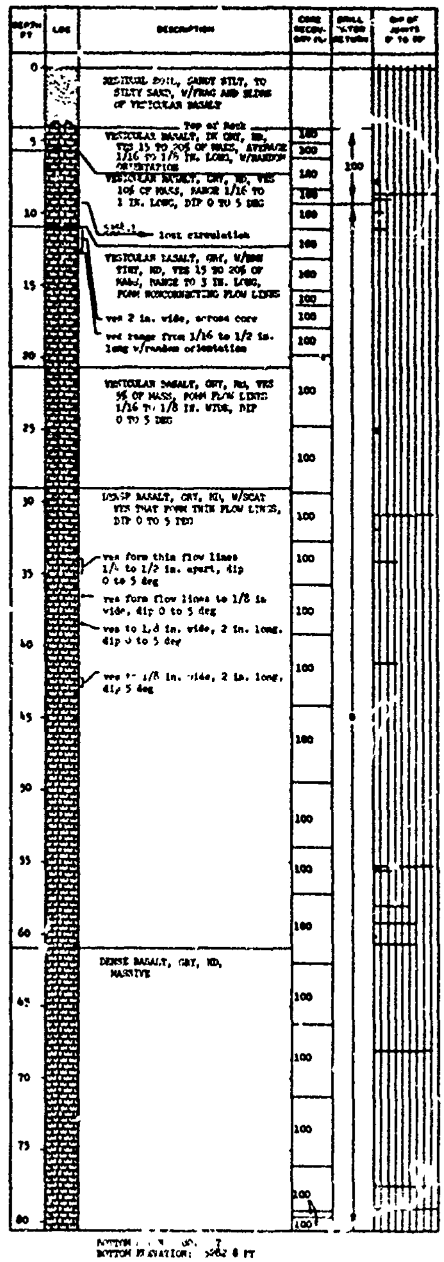
TRAVERSE S-4



NOTE: λ = WAVELENGTHS
V = WAVE VELOCITY

VELOCITY DETERMINATIONS FROM VIBRATORY TESTS
TRAVERSE V-4





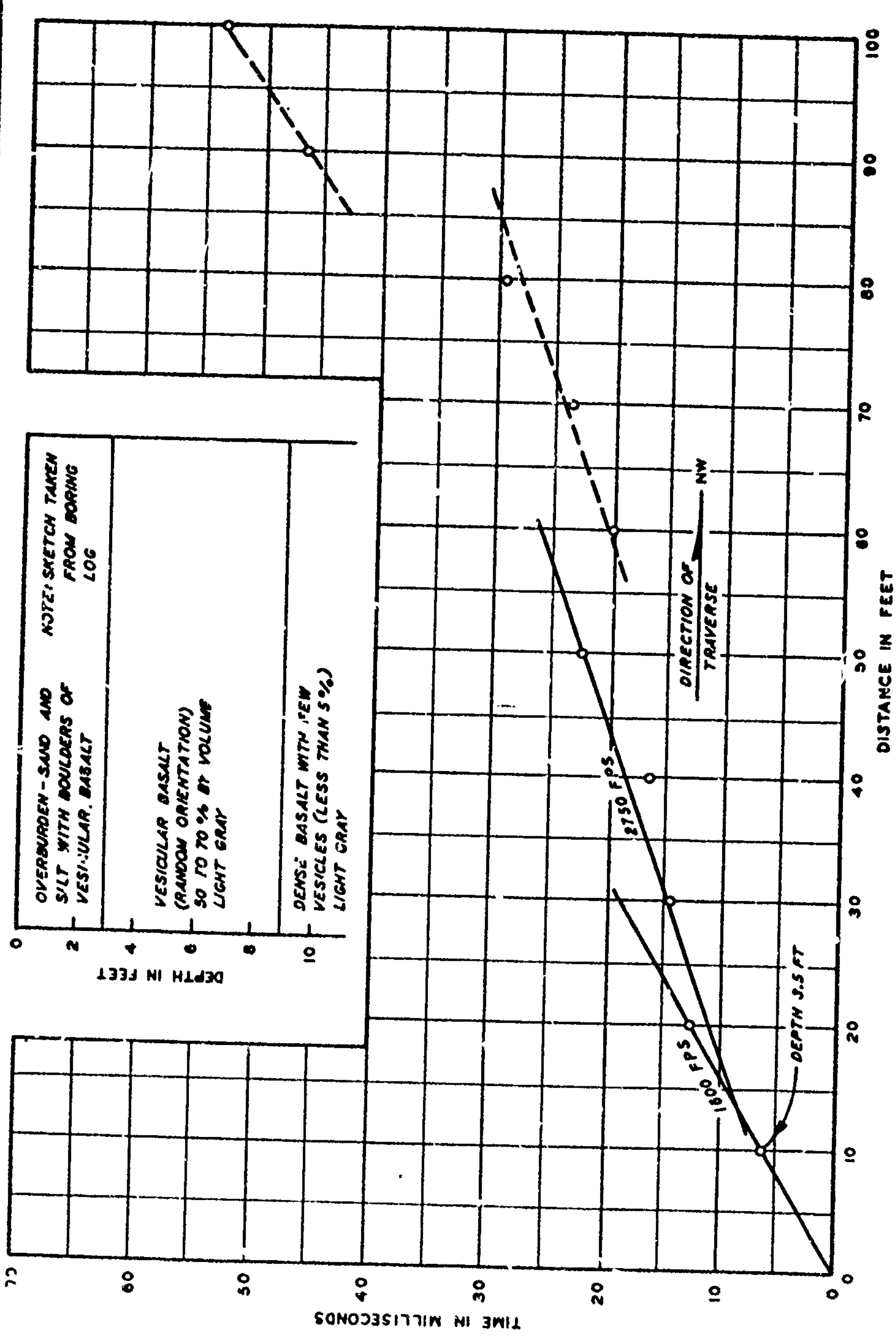
PROJECT PRE-SCHOONER (BUCKBOARD MESA)	
BORING NO [illegible]	
LOCATION NEVADA STATE COORDINATES N 851,[illegible] E [illegible],560 92	
ANGLE OF BORING Vertical	TYPE OF BORING [illegible]
BEARING	DRILLING AGENCY [illegible]
EL TOP OF HOLE [illegible] ft	TOTAL DEPTH 80 [illegible] ft
TOTAL CORE RECOVERY 100 0%	DEPTH TO WATER TABLE [illegible]
HOLE STARTED 29 July 196[illegible]	HOLE COMPLETED 1 August 19[illegible]

BORING LOG FROM SITE 4 AND VIBRATORY VELOCITY VS DEPTH

TRAVERSE V-4

PLATE 17

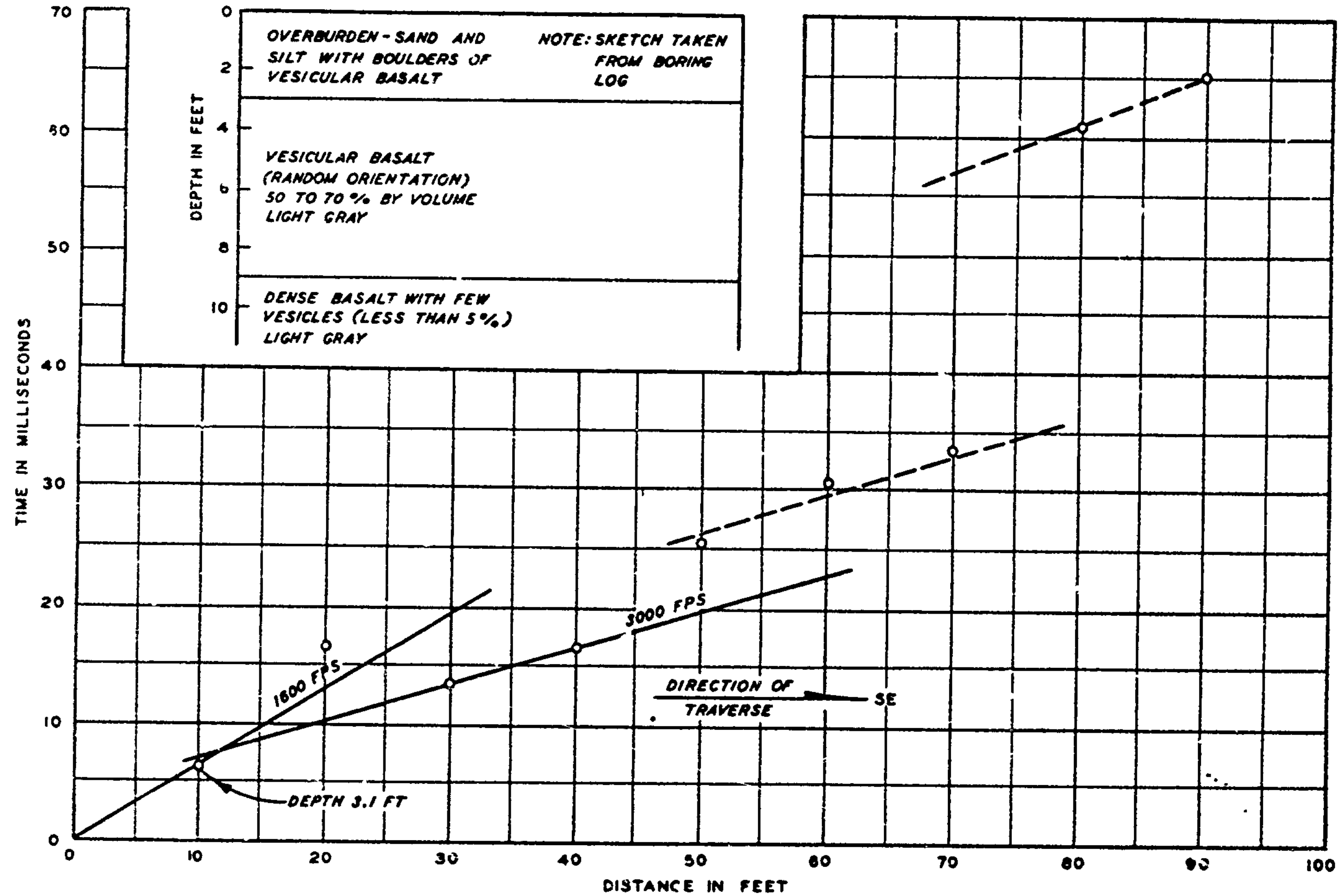
30, 38



VELOCITY DETERMINATIONS FROM SEISMIC TESTS

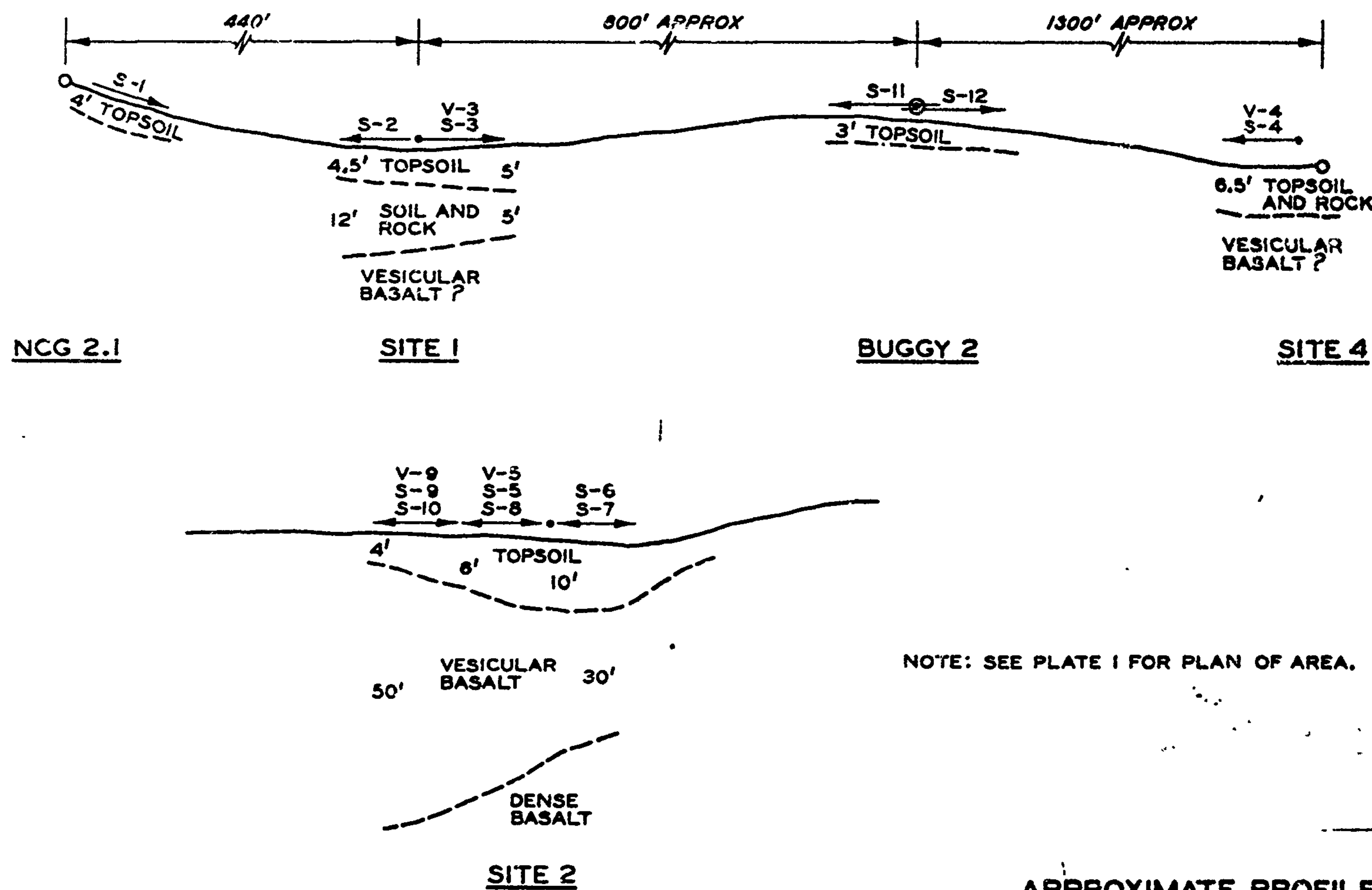
TRAVERSE S-11

PLATE 18



VELOCITY DETERMINATIONS FROM SEISMIC TESTS

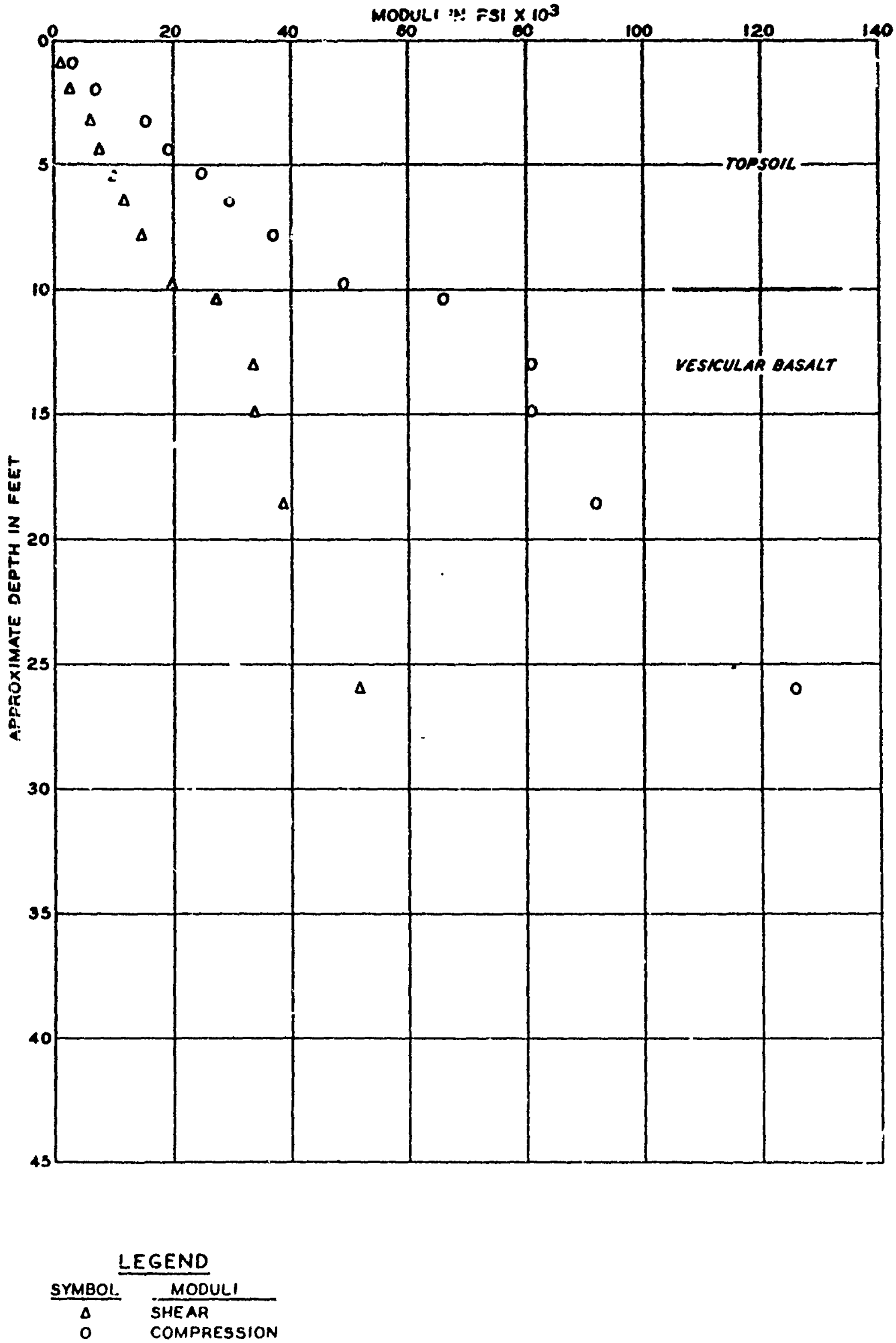
TRAVERSE S-12



NOTE: SEE PLATE 1 FOR PLAN OF AREA.

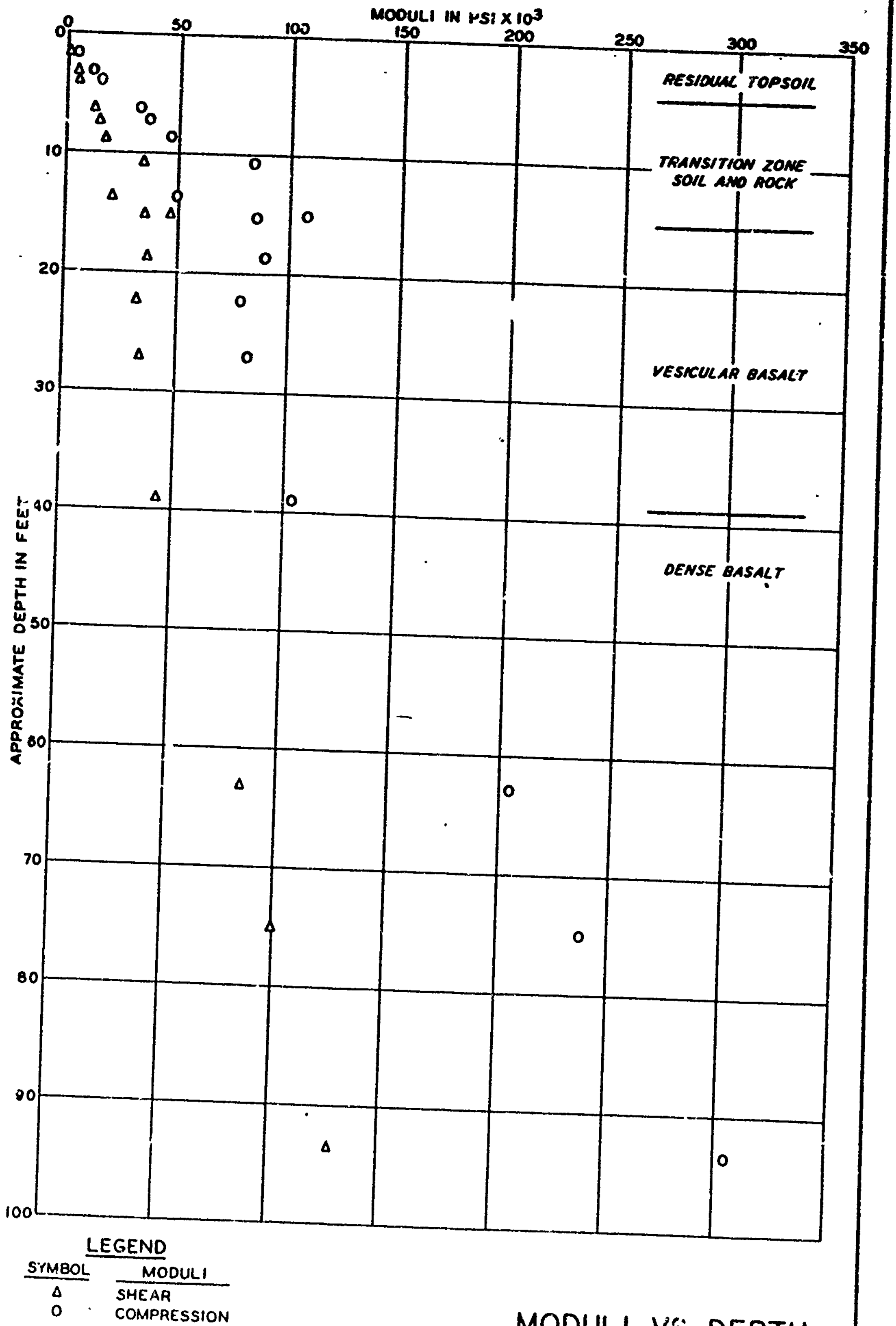
APPROXIMATE PROFILES OF SUBSURFACE MATERIALS
BUCKBOARD MESA

PLATE 20



MODULI VS DEPTH

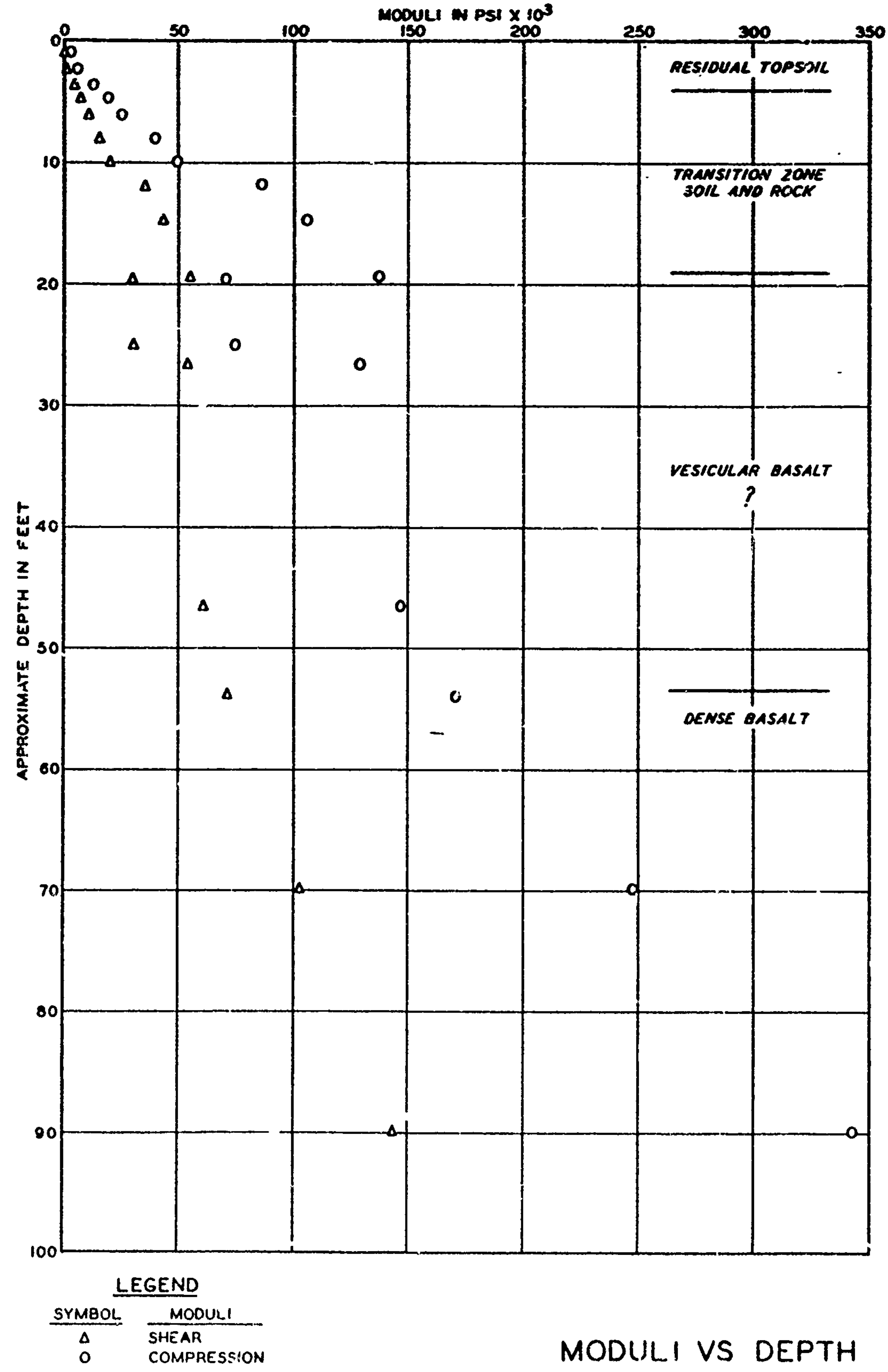
TRAVERSE V-3



MODULI VS DEPTH

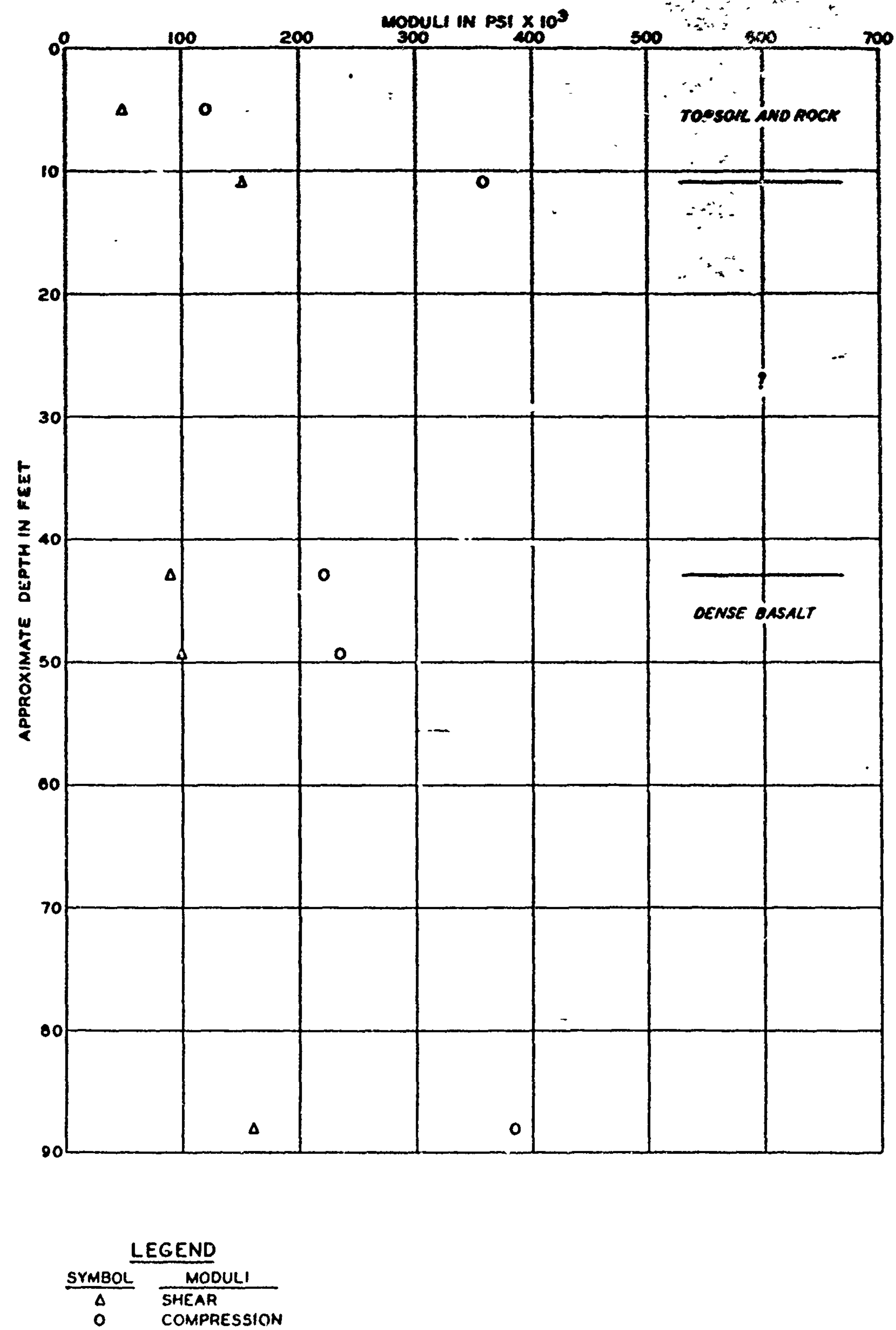
TRAVERSE V-5

PLATE 22



MODULI VS DEPTH

TRAVERSE V-9



MODULI VS DEPTH

TRAVERSE V-4

PLATE 24

APPENDIX A: DETERMINATION OF ELASTIC CHARACTERISTICS OF SOILS BY DYNAMIC FIELD TECHNIQUES

1. This appendix is a résumé of the usual tests performed and methods employed in the investigation of in-situ soils by vibratory techniques. While every test described herein may not be applicable to the study described in the main text, they are presented to describe better the methods and the basic theories on which the procedures are based.

Seismic Tests

2. Seismic tests[1,9*] are made to determine the velocity of compression waves in the soil; this velocity is used in conjunction with other data to determine Poisson's ratio. The seismic data are collected first so that the presence of unusual subsurface conditions, if any, can be revealed, and on the basis of this information the vibration lines can be located to the best advantage. A hammer-type seismograph is used because of its portability, accuracy, and simple and reliable operational features. In practice, a measuring tape is stretched away from a geophone which is embedded in the soil. A 9-lb sledgehammer, incorporating a switch that closes when the hammer strikes a blow, is used as the impulse source. Compression waves are produced by blows of the hammer on a steel plate placed on the ground at regular intervals along the tape. When the hammer strikes the plate, the switch on the hammer closes, activating a binary counter. When the compression wave produced by the hammer blow reaches the geophone, the counter automatically stops, thus indicating the time required for the wave to travel from the point of impact to the geophone.

3. Data are plotted in graphic form as impulse distance versus travel time. The reciprocal of the slope of the lines drawn to connect the plotted points indicates the velocity of the wave through each subsurface medium encountered. A distinct break in the slope of the line

* Raised numerals refer to similarly numbered items in list of references at end of this appendix.

indicates that the wave has probably passed through the interface between two subsurface layers having different velocities. The depth below the surface at which the first interface occurs can be calculated from the following equation:

$$D_1 = \frac{X_1}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}} \qquad \text{(see reference 1)}$$

where

D_1 = depth in feet from the surface to the first interface

X_1 = distance in feet, taken form the origin on the abscissa of the plot of impulse time versus impulse distance, to the point at which the first change in slope occurs

V_1 = compression wave velocity, in feet per second, in first layer of material encountered

V_2 = compression wave velocity, in feet per second, in second layer of material encountered

If a second interface is encountered, the depth can be calculated from the following equation:

$$D_2 = \frac{5}{6} D_1 + \frac{X_2}{2}\sqrt{\frac{V_3 - V_2}{V_3 + V_2}} \qquad \text{(see reference 1)}$$

where

D_2 = depth in feet from the surface to the second interface

X_2 = distance in feet, taken from the origin on the abscissa of the plot of impulse time versus impulse distance, to the point at which the second change in slope occurs

V_3 = compression wave velocity, in feet per second, in third layer of material encountered

If additional interfaces occur, equations are available to determine their depth.

Vibration Tests

4. Vibration tests are conducted to determine both the frequency and the velocity of shear waves in the soil. The vibration tests are performed with a high-frequency electrodynamic vibrator and a low-frequency counter-rotating mass vibrator, in accordance with the procedure outlined in WES

Miscellaneous Paper No. 4-577, A Procedure for Determining Elastic Moduli of Soils by Field Vibratory Techniques. The referenced report explains in detail how wavelengths of propagated Rayleigh waves (treated as shear waves) of known frequency are used to determine the shear and compression moduli of subsurface materials.

Wave propagation

5. When sustained vibrations are induced into a soil, concentric waves are propagated outward from the source. The waves require a time $\frac{X}{V}$ to travel a distance X through the soil in which the wave velocity is V. If the waves are propagated at a known frequency f, then

$$V = \lambda f \qquad \text{(see reference 4)} \qquad (3)$$

where

λ = wavelength, ft

This velocity is dependent upon the ratio of the elasticity of the medium to its mass density ρ, and the wave type. If the shear modulus G is taken as a measure of the elastic properties, the shear wave velocity V_s is defined by:

$$V_s = \sqrt{\frac{Gg}{\gamma}} = \sqrt{\frac{G}{\rho}} \qquad \text{(see reference 4)} \qquad (4)$$

where

g = acceleration due to gravity = 32.2 ft/sec/sec

γ = wet density of soil, lb/cu ft

ρ = mass density = $\frac{\gamma}{g}$

6. In regard to the wave type, R. Jones[6] states that the shear and longitudinal waves produced by the vibrator are radiated into the entire volume of the medium and undergo much greater attenuation than the Rayleigh wave, which is propagated near the surface. Consequently, the vibrations that are detected along the surface of a semi-infinite solid which were produced by a vibrator normal to the surface are almost exclusively Rayleigh waves. Heiland[2] thinks it fairly certain that transverse waves are the most probable. Richart and others,[8] citing Miller and Percy (1955), state that in an elastic solid with a Poisson's ratio of 0.25 for the case of a single

source of vertical load on a free surface, 67 percent of the energy is dissipated as Rayleigh waves, 26 percent as shear waves, and only 7 percent as compression waves. While the ground does not behave in a purely elastic manner, this does indicate that the predominant wave would be expected to be a Rayleigh (surface) wave. However, the differences between velocities of Rayleigh and shear waves with changes in Poisson's ratio are so small as to be of no practical significance in connection with foundation problems. A relation between Poisson's ratio and velocities of propagation of compression, shear, and Rayleigh waves is shown in fig. A1. Since, as shown by fig. A1, the velocities of Rayleigh and shear waves are so similar, the propagated surface waves can be considered to be shear waves for all practical purposes and their velocities can be determined by vibratory tests.

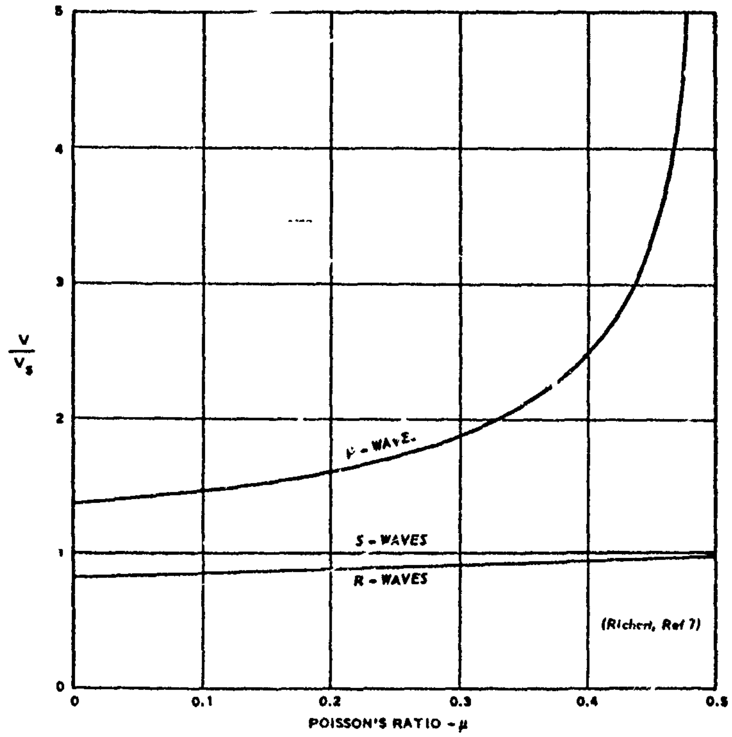


Fig. A1. Relation between Poisson's ratio μ and velocities of propagation of compression (P), shear (S), and Rayleigh (R) waves in a semi-infinite elastic medium

Computation of Poisson's ratio and elastic moduli

7. The velocity of a wave V is determined by the product of the frequency f and wavelength λ. It is then employed in the following

equations which describe the mathematical relation of Poisson's ratio and the compression and shear moduli.

$$\mu = \frac{1 - 2\left(\frac{V_s}{V_c}\right)^2}{2 - 2\left(\frac{V_s}{V_c}\right)^2} \quad \text{(see reference 2)} \quad (5)$$

where

V_s = shear wave velocity, fps

V_c = compression wave velocity, fps

μ = Poisson's ratio

$$E = \frac{2(1 + \mu)\ \rho V_s^2}{144} \quad \text{(see reference 3)} \quad (6)$$

where

E = compression modulus, psi

ρ = mass density of soil = $\frac{\gamma}{g}$ (where γ = wet density, lb/cu ft, and g = acceleration of gravity)

$$G = \frac{E}{2(1 + \mu)} \quad (7)$$

where

G = modulus of shear elasticity, psi

It should be noted here that equations 4 through 7 are for homogeneous, isotropic, elastic materials.

Method of computation

8. The preceding paragraphs have discussed the theory and mathematics utilized in the seismic and vibratory techniques to obtain Poisson's ratio and the elastic moduli of soils. To present and utilize properly the data collected, a definite pattern, or sequence of computation, has evolved as experience progressed.

9. The basic data obtained by means of the vibratory technique are plotted as distances between troughs and peaks as a function of the number

of wavelengths. The wavelength for a particular frequency is determined as the reciprocal of the slope of the line through the plotted data points. The velocity of the shear wave is then determined by equation 3. A compression wave velocity which is determined by the method described in paragraph 3 is used together with the shear wave velocity to determine a Poisson's ratio by equation 5. Caution should be exercised to ensure selection of the shear and compression wave velocities for corresponding media or depths. As an approximation, it can be said that propagation of the shear wave takes place at a depth equal to about one-half the wavelength. Therefore, using one-half the wavelength as the depth at which the velocity of propagation of the shear wave occurs and the velocity of the compression wave at a corresponding depth, a Poisson's ratio can be obtained for materials at different depths. The elastic moduli, E and G, can then be computed by means of equations 6 and 7, respectively. It is usually convenient to plot E and G versus depth, which again is considered to be one-half the wavelength of the shear wave. Such a plot provides a visual picture of the change in soil characteristics with increasing depth. The depth can also be expressed as overburden pressure in pounds per square inch, providing a comparison of E and G with increasing pressure.

Natural Frequency Determinations

10. Simple tests are conducted to determine the natural frequency of the soil. Philips velocity pickups, oriented in both the horizontal and vertical modes, are used to record the ground vibrations. Vibrations are produced by firmly embedding a striking plate in the soil and striking the plate with a sledgehammer, thus producing vibratory waves in the soil which propagate at the natural frequency of the soil. Distance from the velocity pickups to the point of impact will vary, depending upon soil types and conditions. The response of the velocity pickups to the vibration of the soil is recorded on an oscillograph. From this record, the frequency of vibration can be determined. This record can be further utilized to determine the damping ratio of the material in respect to surface waves. The logarithmic decrement can be determined as follows:

$$\text{Logarithmic decrement} = \frac{X_n}{X_{n+1}} \qquad \text{(see reference 5)} \quad (8)$$

where

X_n = an amplitude

X_{n+1} = the succeeding amplitude

The damping ratio ν can be determined as follows:

$$\nu = \frac{1}{2\pi} \ln \frac{X_n}{X_{n+1}} \qquad \text{(see reference 5)} \quad (9)$$

Attenuation Studies

11. Attenuation studies are conducted basically in the following manner. A vibrator is positioned in a strategic location, and velocity pickups or accelerometers are placed along a straight line at known distances from the vibrator. The vibrator is then operated through a range of frequencies, and the response of the transducers to each frequency is recorded on an oscillograph. From these records, the amplitudes of vibrations, at the known distances from the source, can be calculated. These values can then be graphically represented as amplitudes or accelerations versus distance from the source. This graphic representation of amplitude or acceleration as a function of distance will usually lead to the formulation of either an exponential or power equation.

12. Studies have been made concerning the damping of elastic waves in soils[8] in which it was stated that both the horizontal and vertical components of Rayleigh wave amplitude diminish according to the law of annular divergence, i.e. inversely with the square root of distance. This reduction of wave amplitude is due to geometry alone and assumes no damping. Assuming that damping occurs, the amplitude of the propagated wave can be described as follows:

$$y_n = y_1 \sqrt{\frac{x_1}{x_n}}\; e^{-\alpha(x_n - x_1)} \qquad \text{(see reference 8)} \qquad (10)$$

where

y_n = the amplitude at distance x_n

y_1 = the amplitude at distance x_1

α = the absorption coefficient, which corresponds to the coefficient of attenuation, and is a measure of the decay in intensity of an elastic wave with distance

The coefficient of attenuation is related to the logarithmic decrement δ by

$$\delta = \frac{2\pi c\alpha}{\omega} \tag{11}$$

where

c = the phase velocity, fps

$\omega = 2\pi \times$ frequency of the propagating wave, cps

It should be noted that the attenuation of amplitude in the basic assumption is in respect to displacement. However, through known mathematical relations the data can be presented also in terms of velocity or acceleration.

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